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# HILGARDIA

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*A Journal of Agricultural Science*

PUBLISHED BY THE

*California Agricultural Experiment Station*

VOLUME 15

MARCH, 1943, TO FEBRUARY, 1944

With 22 Plates and 75 Text Figures

HHHHHH

UNIVERSITY OF CALIFORNIA

BERKELEY, CALIFORNIA

1944



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# H I L G A R D I A

*A Journal of Agricultural Science Published by  
the California Agricultural Experiment Station*

Vol. 15

MARCH, 1943

No. 1

## • ORIGIN, DISPERSAL, AND VARIABILITY OF THE LIMA BEAN, *PHASEOLUS LUNATUS*<sup>1</sup>

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### ORIGIN AND DISPERSAL

COLUMBUS on his first voyage of discovery found beans under intensive cultivation by the Indians in Cuba. Other early Spanish explorers likewise encountered cultivated beans. English and French explorers, following the Spanish, found beans along the whole Atlantic Coast as far north as Virginia (10).<sup>3</sup> The lima bean, however, appeared to be restricted to the area south of the Potomac River in Virginia, where it is still found in close resemblance to the original primitive forms of the inhabited islands of the West Indies, Brazil, Colombia, Peru, Central America, the western coast of Mexico, and northward to the Hopi pueblos in the southwestern United States. The antiquity of these lima beans is further confirmed by the extensive discoveries of large lima beans of various colors in the tombs of ancient Peruvian cultures (49) and in excavations of pre-Columbian ruins of the southwestern agricultural Indians (38).

It is evident from the records of explorers and botanists that the lima beans have been distributed by man. From these early bean cultures, the lima beans have escaped into the jungles and have established themselves in a wild state where they are recovered at the present time. In North and South America these escaped lima beans are undoubtedly of pre-Columbian origin, but similar escapes are found throughout the world in tropical countries where they have been introduced in post-Columbian times (43).

The origin of the lima bean has been confused. The origin of the large lima has been placed in the Amazon Valley by Bentham (6) and accepted by deCandolle (9) in his studies on the origin of cultivated plants. The small-sized lima beans have been given various origins in the West In-

<sup>1</sup> Received for publication, July 17, 1941.

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<sup>3</sup> Italic numbers in parentheses refer to "Literature Cited" at the end of this paper.

dies and Central America. It is the intention of this study to definitely place the origin of the lima bean and to define the route of distribution especially in pre-Columbian times.

DeCandolle (9), the outstanding authority on the origin of cultivated plants, believed the origin of a cultivated plant could be determined by the discovery of wild progenitors, but unfortunately for this concept some cultivated crops like maize and the common bean (*Phaseolus vulgaris*) have not yielded wild progenitors. Such plants may not have wild progenitors because they may have originated in accidental hybrids which were seized upon and cultivated and improved by primitive agriculturists. The survival of such hybrids may not have been possible in an uncultivated state, a theory accounting for their disappearance. Continued selection under cultivation would tend to produce plants so different as to render identification of relationships doubtful or impossible.

The difficulty of finding a wild progenitor for the cultivated plant was greatly reduced by Vavilov (11), who, aware of this condition, believed that the origin of a cultivated plant could be placed by the concentration of species where only wild forms existed or by the increase in the number of cultivated forms towards the center of origin. He employed, in further defining the origins, the specificity of fungus and insect pests, as well as archaeology. Both the concept of deCandolle and that of Vavilov were successfully employed in the placing of the origin of the lima bean, as will be shown in the evidence to follow.

In a search for the origin of the lima bean, the records of ancient beans found in Peru (49) and in various parts of the southwestern United States (38) were studied. This material, however, was limited and frequently unsatisfactory. It followed, therefore, that the genetic evidence presented by the living material found wild or in cultivation would be of definite assistance. In a search for material the assistance of plant explorers of the United States Department of Agriculture, experiment-station officials, archaeologists, geographers, and botanists in various countries was solicited and abundantly received.

A study of the various forms of lima beans received indicated that the origin could be placed in the general region of Guatemala. A wild lima bean (plate 1, bean 1) recovered a number of times in this area satisfied deCandolle's concept concerning the wild original progenitor. The identification of this wild bean as a lima bean is justified by the fanlike radiations from the hilum indicated by Sturtevant (39) as the most reliable lima-bean character. Plants grown from this seed in the greenhouse made the identification conclusive. This wild lima bean possesses the smallest seed of the species found in any area. The increase in size

of the bean as it radiates from the Guatemalan center further emphasizes this point of origin. The dispersal of the lima bean is undoubtedly due to man. Under cultivation the size and other diversified characters were made to conform by selection to the desires of these primitive plant breeders. The concentration of diversified forms or varieties of lima beans has been found to be greatest in the Guatemalan areas by the Russian plant explorers (8, 45), a finding later confirmed by McBryde,<sup>4</sup> Standley (37), and other collectors. This conclusion concerning the point of origin satisfies the concept of Vavilov, which, taken with discovery of the wild progenitor, likewise agrees with the deCandolle concept and thus places the point of origin of the lima bean undoubtedly in the Guatemalan region.

The dispersal of the lima bean from the Guatemalan point of origin lies wholly in the hand of man under cultural conditions. Two important points related to the dispersal must be considered: first the genetic mechanism by which variations in form and habit may occur for use by the native plant breeders; and, secondly, the lines of dispersal over which the bean could travel. The first condition is answered by the almost general occurrence of hybridization due to insect pollination (5, 28, 29, 30, 20) and by rather infrequent mutations (47, 33).

#### LIMA BEANS IN PRE-COLUMBIAN TIMES

An indigenous bean which had undoubtedly never been under cultivation was found in the Guatemala jungles (plate 1, beans 2 or 45, or plate 2, bean 72). This bean may well correspond to the original bean from which all lima beans were derived.

The lines of dispersal from the point of origin have been defined by collections of wild lima beans, which are undoubtedly escapes from cultivation in pre-Columbian times (plates 1 and 2). The lines consist of three well-defined branches and one spur and are designated as follows: (1) the Hopi, or northern, branch, (2) the Carib, or West Indies, branch, including a spur terminating in Socorro Island about 400 miles off the west coast of Mexico, and (3) the Inca, or southern, branch.

The three lines follow the trade routes rather than travel routes. The Indian tribes along these routes are known to have traded shells and other things, and it is well known that seeds of all kinds were eagerly sought. This desire for new crops persists strongly even today and accounts for the appearance of post-Columbian plants like the watermelon, which apparently arrived in the southwestern United States ahead of European explorers (10).

<sup>4</sup> Collections made by Dr. F. W. McBryde, Fellow in the National Research Council.

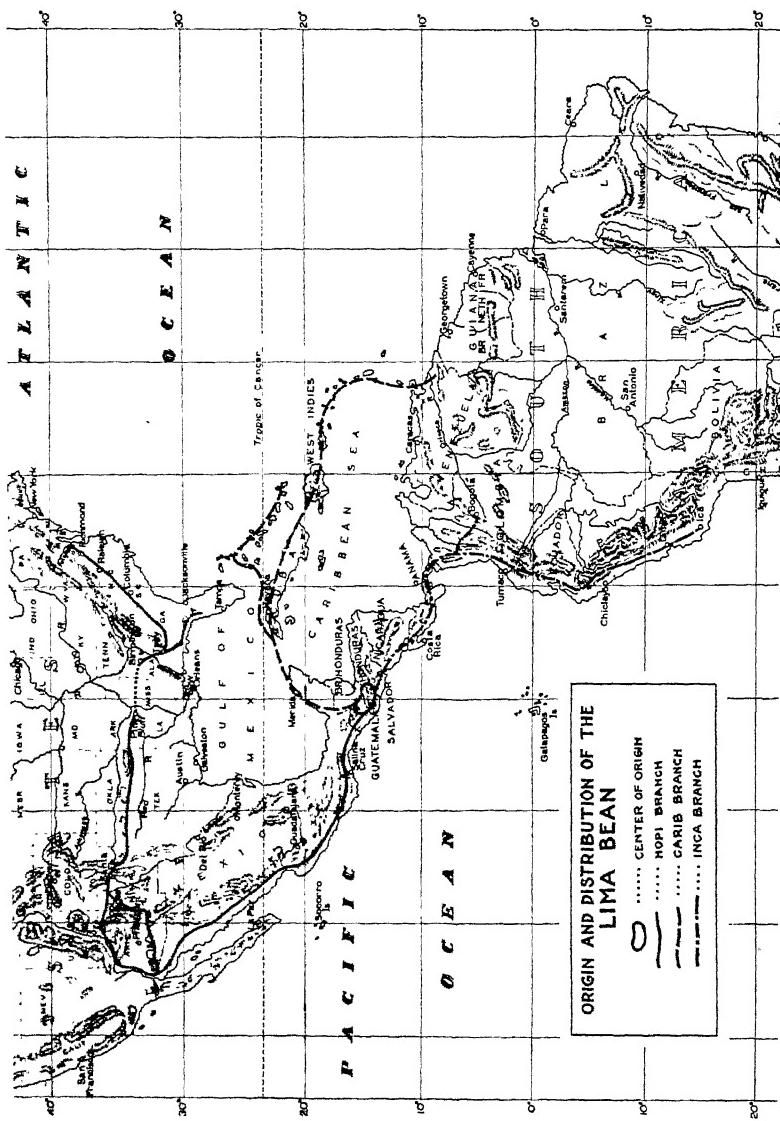


Fig. 1. Lines of dispersal of the lima bean, *Phascolus lunatus*, from the point of origin in Guatemala.

*The Hopi, or Northern, Branch.*—Representative beans of the Hopi branch are shown in plate 1, beans 1 to 43. This branch (fig. 1) proceeded from the Guatemalan point of origin along the western slopes of the Sierra Madre in the zone above the *tierra caliente* as indicated by existing specimens of lima beans recovered from cultivated fields. These beans may have entered the United States by way of Yuma, Arizona, where they have been found, or further to the east by way of the Papago and Pima Indian tribes. The lima beans in the fields of the Papago and Pima tribes and those found in the Hopi pueblos are closely related. That the passage may have been up the Colorado River through the Colorado River tribes and the Walapai (or Hualpai) and Havasupai tribes is indicated by the even closer relationship between the beans grown by the latter and by the Hopi; some doubt exists, however, because of geographical barriers. That these beans have existed in these areas since pre-Columbian times is attested by the lima beans found in pre-Columbian ruins (38). The northward extension was terminated by unfavorable temperatures and high altitudes, for no lima beans have been found in the cliff-dweller ruins at Mesa Verde, although prehistoric specimens of *Phaseolus vulgaris* and *P. coccineus* have been found.

A trade route undoubtedly existed between the Guatemala area northward to the Indian tribes of the Southwest. Corroborative evidence was shown by Sauer,<sup>5</sup> who found in prehistoric ruins the skeleton of a Guacamayo macaw indigenous to southern Mexico and southward. Whiting (48) and others record the finding of Jack beans (*Canavalia ensiformis*) in pre-Columbian ruins.

Wild and cultivated species of *Canavalia* are found today growing in Guatemala. The seed of these tropical species planted in California at Davis did not mature seed owing to photoperiodism, that is the effect of length of day (16), whereas plants derived from seed grown in northern latitudes matured perfectly. This condition indicates that many years or generations may have been consumed in transporting these beans northward to the Arizona sites.

The tepary bean (*Phaseolus acutifolius*) is indigenous to Arizona, where it has no doubt been developed to its present size and productivity by Arizona agricultural tribes. The tepary bean was found under cultivation in Guatemala by McBryde; it differed in no way from certain varieties found today in Arizona. It showed, however, no wide diversity of form and color in the seed, a fact which indicates the southward transportation of the tepary bean along a trade route. On the other hand, the

<sup>5</sup> Collections made by Dr. Carl O. Sauer, Professor of Geography, University of California, Berkeley.

characteristics of the lima beans in the Arizona region are all found in the lima beans of the Guatemala area, but many forms in Guatemala do not occur in Arizona or in the eastward extension of lima-bean culture (plate 1).

The lima beans found by early explorers from Florida to Virginia (10) along the eastern slopes of the Appalachian Mountains differ in no way from those found in the Hopi pueblos at the present time. The lima beans cultivated by the Cherokee Indians of Georgia and other Indian tribes of the Atlantic Coast closely resemble those grown by the Hopi Indians. The route for the dispersal of the lima bean eastward across the Mississippi Valley is obscure and somewhat indefinite. Evidences of bean culture, however, are found as charred remnants in caves (17) as far east as Pine Bluff in Arkansas. A possible route could have passed from the region of Albuquerque, New Mexico, along the Red River skirting the Ozark Mountains. At Rocky Ford, Colorado, Hopi lima beans have become a well-established crop. In the Texas Panhandle and in Oklahoma the Hopi bean has been found well adapted. Other cultures of lima beans were found eastward to the Mississippi River. There still remains a gap across the Mississippi Valley to the western slopes of the Appalachian Mountains (fig. 1). From the southern Appalachians in Alabama into Florida and northward to Virginia, cultivated lima beans identical with those cultivated in the Hopi pueblos are found. In the Gulf states of Mississippi, Alabama, and Florida, Small (35) found similar lima beans; these are still found in a wild state in thickets, undoubtedly escapes from pre-Columbian cultivation (plate 1).

The Henderson Bush (plate 1, bean 39), the first small, or baby, lima to be extensively cultivated in California and elsewhere, started from a chance plant selection in Virginia, originally coming from Indian cultures (18). This variety or others identical in every way with it have been recovered frequently from hybrid Hopi limas.

Over the Hopi trade route may have been carried eastward seeds of common beans (*Phaseolus vulgaris*), corn, and squashes. Along portions of this route, in ancient ruins and middens, have been found shells, flints, beads, and seeds from the Pacific Coast area. The northern California black walnut (*Juglans Hindsii*), extensively used as rootstock for California walnut orchards for the existing groves (36), is found only immediately adjacent to Indian *rancherias* in the Sacramento Delta and in the San Francisco Bay region. This walnut so closely resembles the common black walnut of the Mississippi Valley as to confuse botanists (23) and may well have been carried westward over a trade route.

Gilmore (17, 42) presented a possible route for corn arriving from

Mexico at Del Rio, Texas, and following along the Edwards escarpment to the Red River and thence eastward. He was not entirely satisfied with the route, and it appears more probable that the Hopi trade route was used not only for lima and common beans but for corn and squashes.

*The Carib, or West Indies, Branch.*—From its initial start in Guatemala, the Carib branch passed along the western slopes of the mountains to the lowlands of the Isthmus to Tehuantepec (8, 37), across to the coast of the Gulf of Mexico, and thence easterly along the dry calcareous lands of Yucatan, where Standley (37) and Bukasov (8) found lima beans in both the wild and cultivated state. Apparently this route is the only one eastward, except the Hopi route, which possesses climatic conditions suitable to the lima bean. The eastern slopes of the Sierra Madre are nowhere favorable to lima beans in the wild state. The reason appears to lie in the excessive rainfall or humidity throughout the year, for the lima bean requires a somewhat arid climate for a portion of the year. The arid condition of the Yucatan peninsula favors the culture of lima beans. From the easterly tip of Yucatan the lima beans were undoubtedly transported in the canoes of the Carib Indians to Cuba and thence to all the islands of the West Indies where they have been found. This route lay by way of the Greater and Lesser Antilles to the northern coast of South America. From this point the lima bean has probably been extended to all parts of Brazil where it has been found by various botanists (14, 6, 27). Evidently, however, the rainy basins of the Orinoco and Amazon rivers were unfavorable to it, for no wild limas are found in these regions. Pittier (32), who has made extensive studies of beans in Costa Rica and elsewhere in Central America, reports that no wild limas were found in Venezuela proper, and only on two small islands off the northeast coast have wild beans been recovered.<sup>6</sup>

In tracing the Hopi and Carib branches (fig. 1), it will be noted that the distance between Cuba and Florida is very short; yet the lima beans of Florida and Cuba are definitely of distinct groups. The moist lowlands of southern Florida are unfavorable to lima beans. This condition could have been overcome if water travel had carried the Carib type of lima bean to northern Florida. This gap, however, was not bridged, as evidenced by the distinct differences between the groups of lima beans.

The Hopi branch is usually rather flat and medium in size, whereas the Carib branch, as was found by Bukasov (8) in Yucatan, includes many oval or roundish beans of the potato type, frequently of bright-red color, characters absent in the Hopi limas. Typical shapes and colors of the Carib branch are shown in plate 1, beans 44 to 53, and plate 2, beans

<sup>6</sup> H. Pittier, letter to W. W. Mackie, dated April 20, 1939, at Carácas.

54 to 70. The greatest and most distinctive difference lies in the cyanide content. All lima beans contain cyanide, due to the glucoside, linamarin. Lethal doses of this poison in Puerto Rico and elsewhere have been reported. This condition led to an extensive survey of the cyanide content of lima beans from all areas for the three branches, but only in certain varieties of the Carib branch was the content sufficiently high to be dangerous as human food. The high cyanide content appears to be inherited, for not all varieties of the Carib branch contained dangerous quantities. The linamarin of lima beans will be discussed further under "Cyanide Content."

Wild lima beans collected on Socorro Island of the Revillagigedo group in the Pacific Ocean by Mason (24), on a botanical expedition, appear to be a spur of the Carib branch; for they differ from the Hopi branch, to which they are closer geographically, in the flatness of the seed and the high cyanide content. Evidence of the latter is the poisoning of the crew of Captain Colnett's (12) expedition in 1798 by eating wild lima beans found growing on the island. The beans seem to have arrived here at an early date. That they were brought to the island by Indians in canoes is very probable, for the author can vouch for the seaworthiness of the Indian canoes from personal experience. The beans (plate 1, bean 46) are only slightly larger than the wild progenitors in the jungles of Guatemala. They are perennial and truly tropical in habit. Seed collected by Mason would not fruit under California conditions, owing to photoperiodism.

*The Inca, or Southern, Branch.*—Like all other lima beans, the Inca branch originated in the Guatemala region. This branch (representative beans are shown in plate 2, beans 71 to 96) is best distinguished by the extreme sizes reached in pods and seeds—the largest bean (plate 2, bean 93) being over 31 times the weight of that of the small, wild progenitor of all lima beans (plate 1, bean 1). An increase in size of seed or fruit is usual in the processes of breeding by selection. The passage of maize southward from the Aztec to the Inca civilizations shows a great increase in the size of seed and plants, culminating in the large-seeded Cuzco floury maize of Peru.

McBryde found a wild lima bean of large size but flat, thin, colored, and mottled (plate 2, bean 78); this may well have been the type from which the large lima bean descended.

In the passage southward through Central America, Colombia, Ecuador, to its final termination in Peru, many forms, sizes, and colors were retained. These forms find their widest range and highest altitude in Colombia in the region of Bogotá. As the culture of the lima bean passed

southward into the more arid and unfavorable regions of Peru, the plant breeding for adaptation was intensified. The culmination of these breeding efforts was reached in the region of Ica on the coast south of Lima, Peru. Here the long, cool, dry summers resulting from the upwelling of the Peruvian, or Humboldt, Current forced the very restricted adaptation found in the modern large lima beans, all of which originate from this source.

Many colors, including red, black, brown, and mottlings thereof, have been recovered from ancient Peruvian tombs (49). The preference for white over color in these large lima beans appears to be related to the ease by which this color is fixed, for it is recessive to all other colors. Various colors and mottlings are still found in the Inca group.

The fact that continued increase in size can be achieved by breeding indicates that a number of factors, or genes, are involved; polyploidy is not involved, for the chromosome number has never been found to change (25). The potato, or oval, shape of seed probably appeared among the progeny of field hybrids and was selected by ancient plant breeders. The effect of early breeding upon modern varieties will be discussed under dispersal in the following section.

#### LIMA BEANS IN POST-COLUMBIAN TIMES

Since the discovery of America, lima beans have been widely distributed, especially in the tropics, where they find conditions closely resembling those where they originated. Each of the three branches—Hopi, Carib, and Inca—has contributed to modern horticultural varieties. It is possible to determine with a fair degree of accuracy from which branch a modern horticultural variety has been derived.

The Hopi branch was first encountered in post-Columbian times along the Atlantic Coast. From the Indian tribes found cultivating lima beans, such varieties as Jackson's Wonder, Sieva, Small White, Carolina, Carolina Sewee, Willow-leaved, Henderson Bush, Woods' Improved, and many others have been derived. Lima beans grown by the Hopi and southwestern Indians were the basis for several varieties bred by the author. These varieties include Hopi 2000, Hopi 155, Hopi 56, Hopi 5989, and Hopi 12. All of these possess various degrees of resistance to the attacks of the root-knot nematode and have been of outstanding value in areas badly infested with this pest.

The color patterns of the seed coats of the varieties found among the Hopi pueblos so closely resemble those of similar varieties derived from the Indians of the Atlantic Coast that sharp distinctions are not possible. The author has selected, from Hopi strains heterozygous in the field,

such types as Jackson's Wonder, Henderson Bush, Willow-leaved, and many others. At the same time, such types as the sulfur-backed, green-eyed Hopi 2000, Brown Hopi, Red Hopi, and Red Mottled Hopi—all of the medium-sized seed type—have not been recovered from the Atlantic seaboard (plate 1). It appears from these and other observations that this and other types found in the Hopi agriculture did not pass on to the Atlantic Coast. This condition agrees with Vavilov's concept which provides for a reduction in the number of forms as the culture is extended from the common center of origin.

The Carib branch in post-Columbian times has been widely dispersed. It is distinguished not only by the bright-red-colored types but principally by the occurrence of types or varieties bearing cyanide in lethal amounts. Inasmuch as the first explorers in America encountered the Carib branch, it has become widely distributed, especially in tropical areas over the whole world. The Manila galleons in their passage across the Pacific from the Philippine Islands to Mexico transported lima beans of the Carib branch from the West Indies. These limas escaped from cultivation and became established in the Philippine Islands and in near-by regions. Probably from this source also came varieties of the group found at present in Java, Burma (41), Mauritius (47), and other East Indies areas. Many varieties of lima beans found in the East Indies have been reported as bearing excessive quantities of cyanide (11). In Africa also (43) varieties of the Carib branch have been recovered, but the direct connection with the West Indies has not been recorded. It is likely that these lima beans were carried to various parts of Africa from Brazil through the slave-trade operations as was the peanut, which reached interior African tribes ahead of the first European explorers. Further explorations will doubtless extend the range of this group in tropical areas.

The Inca branch in the post-Columbian period has given to horticulture the largest number of varieties and has received the most widespread and extensive distribution of all the lima beans. All the modern varieties of large lima beans trace back to Peru, and these in turn to a Guatemalan origin. The discovery of large lima beans of various types in the ancient tombs of Peru (49) points to the vast age of this branch and indicates the fixity of many characters such as color, size, shape, and adaptation to the peculiar climate of the Peruvian coast, where the modern large lima bean was developed subject to the influence of the Peruvian Current. The persistence of these characters has restricted the commercial production of dry limas (the Inca, or large-lima, type) to areas with climates somewhat similar to that of the Peruvian coast.

Many varieties (18, 19, 43) have been introduced into Europe and into the eastern United States from Peru, but beyond affording varieties restricted to gardens, they have not become established as a major crop. In Madagascar, Peruvian large limas were introduced at an early but unrecorded date. The identification of the Madagascar large lima with the Peruvian bean is complete, for the whole list of characters found in the Peruvian types are also found in the Madagascar large-lima varieties. On this large island in the southern part of the Indian Ocean conditions exist which satisfy the requirements of this exacting bean. According to Rimbaud (33) the long growing season common to the Peruvian types was found undesirable in certain Madagascar districts because of water shortage. Taking advantage of variability due to heterozygosity common to lima beans, the Madagascar farmers on the southwestern arid coastal areas established early-maturing varieties by plant selection. In some of these varieties early maturity was linked with smaller size of seed and smaller vines. It was probably one of these varieties that was the foundation of the large-lima-bean industry in southern California. The first of these introductions was made, according to accepted reports, by the captain of an American clipper in the Mexican era before American occupation of California. Forms of these early-maturing Madagascar large lima beans were recently tested in Ventura County and found to resemble closely the Lewis variety (19) from which the majority of field varieties grown in California originated.

- In Burma (41) lima beans have been grown extensively, but in these beans cyanide frequently appears in dangerous amounts. This indicates that they may have been derived from the Carib branch; but their present large size perhaps points to a cross in the field with beans from the Inca branch (29, 20).

The greater number of the large-lima-bean varieties offered by seedsmen in the United States have arisen from plant selections made in California. The practice of contracting with California lima-bean farmers for seed of varieties of large lima beans grown in gardens in the eastern states furthered the creation of new varieties by plant selection. This process is made possible by field crossing due to insects (28, 30); crossing may occur not only within a group such as sievas but also between the sieva and large-lima group.

#### CLIMATIC ADAPTATIONS

The lima bean, as indicated by its behavior in its place of origin in Central America, is a perennial viny plant, usually with an enlarged rootstock for the storage of starch. Annual and small bush forms, how-

ever, have appeared after hybridization. Only in tropical or subtropical areas does it escape from cultivation and maintain itself in a wild state. Low-lying coastal areas of the *tierra caliente* are not usually acceptable to the lima bean, which prefers sloping or well-drained areas above the *tierra caliente* to an altitude of 6,000 feet in the tropics and of 3,000 to 4,000 feet in some of the temperate zones. Climates best suited provide a dry season for the maturing of the seed. Ability to withstand severe drought until the next rainy season is characteristic. In the hands of the Hopi and other southwestern tribes, the lima bean produces crops without irrigation, the crops depending entirely upon the scanty rainfall of these arid regions. Cultivation is scanty and consists almost exclusively of planting, of weed eradition, and of protection against wind. Hopi limas surviving these severe conditions have provided hardy stocks useful in breeding against drought and diseases.

The sieva, or small-lima, group includes varieties much more resistant to heat and arid conditions than the large-lima group. On this account many of these varieties can thrive in the more continental climates of the interior. For this reason the sieva varieties are spread over a wide range in North America, Central America, South America, and the West Indies. On the other hand, the large-lima group is restricted to the coastal areas, where extremes of heat do not occur and where the air is more highly charged with moisture, usually in the form of fogs, in the growing season. Both groups are fairly drought-resistant, and for this reason the perennial types survive and thrive where rainfall is deficient over a considerable portion of the year. The perennial habit, which is the usual form for the wild limas, is found in both large- and small-lima groups. In resistance to cold there appears to be little difference.

The lima bean usually requires a long growing season free from frost, varying from about 100 days for the earliest varieties grown in the United States to seven to nine months for the large-lima varieties of Madagascar and Peru. At maturity the pods of many of the wild types shatter badly in rainy seasons; but selective breeding has provided non-shattering varieties under cultivation.

Photoperiodism, or the effect of length of day upon plants, is pronounced in lima-bean varieties long established in the tropics. Such varieties when planted in temperate zones do not fruit until the lengths of day and night are about equal. Garner and Allard (16) noted this effect in beans from Peru and Bolivia. This condition prevents the production of seed in the temperate zones because of the appearance of cold weather and frost before normal maturity has arrived. All wild lima beans from the tropics show this behavior; they completely fail to

fruit. Some of the cultivated varieties, however, ripen seed; from this seed, plants were secured that possessed disease and pest resistance. Lima-bean seed originating in the temperate zones did not fail to set seed in the normal manner. How much time is required to correct the effect of photoperiodism in the passage of the beans northward from Guatemala cannot now be calculated, but undoubtedly a long time was required. The separation of the Carib and Hopi branches by photoperiodism is sharply marked, for this response is usually found in all the Carib beans grown in the tropics and never in the Hopi beans from the north temperate zone.

#### CYANIDE CONTENT

The specific unity of lima beans is indicated by a common physiological character, the occurrence of cyanide containing the glucoside, linamarin (2). The glucoside is common to all lima beans and imparts the characteristic flavor that is absent from other species of beans.

Cyanide, however, is found in many fruits and in forage plants, including the almond, peach, apricot, and sorghums. The flavor which the linamarin imparts is, when the amount is not in excess, desirable and in no way injurious. The Pure Food Law of the United States places the limit for the injurious quantities to humans at 100 p.p.m. of HCN. In Puerto Rico, McClellan reports that 300 p.p.m. of HCN was lethal when fed to chickens and killed most of them. Reports from this area and others of lethal effects on humans have been recorded. One lot of wild lima beans from Puerto Rico analyzed 970 p.p.m. cyanide as HCN and gave off the characteristic bitter-almond odor when briskly rubbed (plate 1, bean 47). In Burma (11, 46) considerable trouble was occasioned by excessive quantities of cyanide, which frequently prevented export. In India the same trouble arose from lima beans of the roundish small type—both red and white—in seed from Mauritius that evidently derived from the Carib branch.

A careful survey of lima beans of all classes grown in California demonstrated conclusively that no varieties derived from either the large (Inca branch) or the small (Hopi branch) limas contained dangerous quantities of cyanide, the quantity ranging from 25 to 55 p.p.m. as HCN, which is far below the limit of tolerance set by law (100 p.p.m.). In order to determine the effect of tropical environment upon cyanide content of lima beans, standard varieties of large and small limas of the United States were grown in experiment stations in the coastal regions of Georgia and at Mayaguez, Puerto Rico. The seed from the resulting crops in both areas contained, on analysis, slightly lower quantities of

cyanide than the original seed from California. Large lima beans from Madagascar showed no objectionable quantities of cyanide (25 to 75 p.p.m. as HCN). The Madagascar beans are unquestionably from the Inca group and have been grown in the tropics for a long time. It becomes apparent from the evidence that different degrees of cyanide content may be inherited as genetic characters. Control of cyanide content may therefore be effected by breeding methods.

#### DISEASES AND PESTS CHARACTERISTIC OF LIMA BEANS

Disease and insect pests are frequently specific and to this extent may be used to distinguish host species. The genus *Phaseolus* is divided into two groups of species—Asiatic and American. The most important group includes those originating in the Americas, such as *Phaseolus vulgaris* (kidney bean), *P. lunatus* (lima bean), *P. coccineus* (multi-florus, or butter, bean), and *P. acutifolius* (tepary bean). The Asiatic group indigenous to that continent includes *P. Mungo* (urd bean), *P. aureus* (mung bean), *P. angularis* (adzuki bean), *P. calcaratus* (rice bean), and *P. aconitifolius* (moth, or mat, bean). These Asiatic species are all susceptible to the fungus disease caused by *Cercospora cruenta* (21) but not to *Gleosporium lindemuthianum*, whereas the American species are resistant.

While many general fungus diseases, like *Fusarium martii*, *Rhizoctonia solani*, and *R. bataticola*, and pests, including wireworms, root-knot nematodes (p. 15), red spider, and thrips attack the lima bean, many diseases and pests are more specific. The lima bean downy mildew caused by *Phytophthora phaseoli* (40), scab caused by *Elsinoe phaseoli* (7, 22), and pod blight caused by *Diaporthe phaseolorum* appear to be specific for all lima beans. The lima bean pod borer, *Etiella zinckenella* (13, 4), harbored by native lupines, confines its attacks principally to all types of lima beans. The specificity of these diseases and pests further tends to establish the unity of all lima beans as one species.

#### INHERITANCE OF SOME IMPORTANT GENETIC CHARACTERS

In breeding for disease resistance and improvement in yield and quality, hundreds of crosses were made with the usual fertility found in hybrids made within the same species. The chromosome numbers for all lima beans is the same—namely, haploid 11 and diploid 22 (25, 34). The following genetic ratios were found in lima beans whether the

crosses were made between varieties of a single group or between varieties of opposite large- and small-lima groups usually classified as distinct species.

Vine dominant over bush . . . . .	ratio 3 : 1
Color dominant over white . . . . .	ratio 3 : 1
Flat, thin seed dominant over potato type . . . . .	ratio 3 : 1
Mottling dominant over self-color . . . . .	ratio 3 : 1
Colored inflorescence dominant over white . . . . .	ratio 3 : 1
Broad leaf dominant over willow leaf . . . . .	ratio 15 : 1
Size intermediate in F <sub>1</sub> . . . . .	multiple factors
Resistance to root-knot nematodes dominant . . . . .	multiple factors

Anthocyanin color in leaves and stems is lethal to the plant in the homozygous condition.

Although this list is limited, it shows no inherited difference that would warrant species distinction. Further genetic studies now being carried on seem unlikely to disturb this conclusion.

In all the groups of lima beans, strains or varieties have been found resistant to the root-knot nematode. The first discovery, made by the author in 1923, arose when breeding lima beans from the Hopi Indians in northern Arizona (15). A number of varieties were recovered, like Hopi 2000, but others like Hopi 155 (plate 1, bean 42), Hopi 5989 (plate 1, bean 41), and recent crossings with the common Wilbur (plate 1, bean 40), were created by hybridization.

In an endeavor to place nematode resistance in large lima beans, crosses were made with nematode-resistant Hopi varieties. In back-crossing these hybrids to the large lima, it was found that size was increased only slowly and with difficulty, owing to the multiple factors involved. From an importation from Peru of a mixed lot of large lima beans, a plant was discovered which bore very large seeds and possessed superior resistance to nematodes. This strain, in addition, developed considerable resistance to wireworms. Even though five years of breeding for nematode resistance in large limas was involved, it was found desirable to start breeding afresh, using the new nematode-resistant Peruvian large lima.

Tests with small limas yielded a number of nematode-resistant forms, one of which showed the highest resistance yet discovered. The multiple factors which combine to produce nematode resistance in lima beans appear to be the same in all lima beans and provide convincing evidence of the unity of the species.

## NOMENCLATURAL HISTORY AND PRESENT TAXONOMIC STATUS

The lima beans encountered by the early explorers included many forms and colors in seeds and various forms of vines. These were frequently interpreted as multinomial species by the pre-Linnæan botanists. The drawing of a bean vine and seed in Lobel's *Icones* (18) is undoubtedly that of a small-podded, or sieva, lima, bearing the name *Phaseoli parvi pallidoalbi ex America delati*. Clusius, 1601, noted many forms of vine and colors of seed. Bauhin, 1651, and others listed several forms. Linnaeus, 1753 (26), in his book *Species Plantarum* listed two species—*Phaseolus lunatus*, a small, or sieva, lima and *P. inamoenus*, a large lima.

A post-Linnæan chronological list of lima-bean species compiled by Van Eseltine (43) includes the following:

- Linnaeus, 1753  
*Phaseolus lunatus*—small white sieva  
*P. inamoenus*—speckled large lima
- Jacquin, 1770  
*P. rufus*—red sieva, or Mauritius bean  
*P. bipunctatus*—spotted sieva
- Medicus, 1787  
*P. achariensis*—sieva
- Louriero, 1790  
*P. tunkinensis*—red-mottled sieva
- Moench, 1794  
*P. macrocarpus*—large, speckled
- Zuccarini, 1809  
*P. Xuarezii*—dwarf or bush sieva
- Stokes, 1812  
*P. saccharatus*—sieva  
*P. parviflorus*—sieva
- Poiret, 1813  
*P. macrocarpus*—large white
- Schrank, 1819  
*P. derasus*—black-seeded Brazilian sieva
- Kunth, 1823  
*P. puberulus*—yellow sieva
- Roxburgh, 1832  
*P. maximus*—large white
- Blanco, 1837  
*P. ilocanus*—red-mottled sieva  
*P. vezillatus*—large white

## Macfayden, 1837

- P. dumosus*—large white
- P. limensis*—large, white, plump seed
- P. foecundus*—large, oval, white
- P. saccharatus*—white or red sieva
- P. latisiliquus*—large white

## Bentham, 1859

- P. lunatus*—small-podded sieva
- P. bipunctatus*—as synonym
- P. lunatus* var. *macrocarpus*—large-podded

## Bailey, 1924

- P. lunatus*—small-podded sieva
- P. limensis*—large-podded

## Piper, 1926

- P. lunatus* L.—all lima beans

## Van Eseltine, 1931—five formae

<i>P. lunatus</i> forma <i>macrocarpus</i>	Van Esel. flat lima
<i>P. lunatus</i> forma <i>salicis</i>	Van Esel. willow leaf
<i>P. lunatus</i> forma <i>lunonanus</i>	Van Esel. bush sieva
<i>P. lunatus</i> forma <i>limenanus</i>	Van Esel. bush lima
<i>P. lunatus</i> forma <i>solanoides</i>	Van Esel. potato lima

Beginning with those described by Linnaeus, the 26 variously listed "species" may be included in two groups: the large-podded and the small-podded types. Species distinctions made by the various botanists were based on characters that do not warrant species rank, as was shown in the preceding section. The basic distinctions included vine variations (bush, vine, and intermediate), annual and perennial habit, leaflet form (willow leaf, large and small size), size and shape of pod, pod points, number of seeds per pod, warty serrations on pod sutures, seed-coat-color distributions, radiations from the hilum, shape of seed, including flat, oval, and others. Bailey (3, 4), following the example set by Linnaeus (26), recognized two forms—the large-podded type, which he listed as *Phaseolus limensis*, and the small-podded types, which he included under *P. lunatus*. Piper (31), who devoted years of research to the study of American Phaseolinae, states: "This is a very diverse aggregation of both wild and cultivated forms, whose status is variously interpreted by different botanists. In the writer's judgment, it is but a single botanical species." Van Eseltine (43), who concurs in Piper's concept of a single species for lima beans, employs five "formae" to include the many genic variations. The formae are outlined as follows:

*Phaseolus lunatus* L. The small lima, or sieva, bean. The leaves of the typical forma are relatively thin and small, as are the pods.

a) Forma *macrocarpus* Van Esel. Flat lima. Pods and leaves are thicker and larger than are those of the typical form.

b) *Forma salicis* Van Esel. Willow leaf. This forma has narrow lanceolate leaflets, but otherwise resembles true *lunatus*.

c) *Forma lunonanus* Van Esel. Bush sieva. This dwarf forma arises from the production of inflorescences from both the terminal and distal axillary buds after the plant has developed from 4 to 8 nodes. This forma also includes a type in which the first 3 or 4 nodes produce long axillary branches.

d) *Forma limenanus* Van Esel. Bush lima. Dwarf limas are counterparts of the preceding form, except for pod and leaf characters.

e) *Forma solanoides* Van Esel. Potato lima. This forma has leaflets somewhat narrower and more triangular than those of the flat limas, the pods are slightly shorter, and the seeds are more nearly circular in cross section. Otherwise the plant resembles the true lima.

These five formae, which appear to be six if the sieva, or small-podded, lima is included, offer no more marked or serviceable distinction for botanical rank than do the usual horticultural varieties. For example, formae *a* and *b* are both large limas, separated on the shape of the seed, the former being flat and the latter more nearly globular. These characters have been exchanged from vine to bush by artificial hybridization, at which times all intermediate shapes were isolated. The same situation holds true in regard to forma *b* and other types of leaflets. This willow-leaf forma has been transferred to many types or varieties of lima beans in the large and small groups. Likewise formae *c* and *d* are separated as sieva bush and large-lima bush, respectively. The bush character, which appears the same in both large and small limas, has been transferred by breeding methods at will into any form of lima bean as a single character, or gene. None of the five formae are separated on a basis which cannot be restricted to a comparatively few genes.

Bailey (3, 4), in support of his separation of lima beans into two species, used certain distinctions which Van Eseltine (43) has tabulated:

	Large lima ( <i>Phaseolus limensis</i> )	Sieve, or small, lima ( <i>Phaseolus lunatus</i> )						
Duration . . . . .	Perennial	Annual						
Calyx . . . . .	Linear	Ovate						
Bracts . . . . .	One third length of calyx; not strongly veined	Nearly, or quite, equaling calyx; strongly veined						
Pod . . . . .	Thick-edged; blunt, short tip	Thin-edged; sharp, long beak						
Leaves . . . . .	3 to 5 inches long; thick	2 to 3½ inches long; thin						
Seeds . . . . .	<table border="0"><tr><td style="padding-right: 10px;">White</td><td>Various colors</td></tr><tr><td style="padding-right: 10px;">Plump</td><td>Flat and thin</td></tr><tr><td style="padding-right: 10px;">Larger</td><td>½ inch long</td></tr></table>	White	Various colors	Plump	Flat and thin	Larger	½ inch long	
White	Various colors							
Plump	Flat and thin							
Larger	½ inch long							

While Bailey has endeavored to place all lima beans under two species conforming to the commercial groups of large and small, or baby, limas, this species distinction is not borne out by the character differences in the forms now available. For example, perennial and annual forms have

been found in both large- and small-podded types, although perennial forms appear more common. In certain protected areas of California, perennial types of limas have persisted.

The linear and ovate forms of calyx bracts and bract veins are not sufficiently defined for species distinction. Bailey found the broad calyx form included 76 per cent of the sievas and 66 per cent of the large limas.

Pod distinctions, however, appear more strongly marked, and the groups with large and small pods are further set apart by the length and sharpness of the pod points.

Leaf characters which Bailey uses are not sufficiently distinct for use in this separation. The size of the leaf in many cultivated large limas is greater than that of the commonly cultivated small-podded lima. On the other hand, collections of lima beans from a wide range of sources present a contrary set of evidence, for many small-podded limas possess the largest sizes of leaves. Willow-leaf types as well as intermediate grades are found in both classes. Very dark-green colors, commonest in the small-podded types, are also found in the large-podded types.

Seed color as a basis for species separation is completely unjustified (plates 1 and 2), since all possible colors, shades, and mottlings are found in both groups. The shape of the seed likewise fails. All shapes occur in both groups. For example, the potato type (Van Eseltine's forma *solanoides*) occurs naturally in both large and small limas, and can be transferred at will by artificial crossing. Size, however, is more reliable for group separation, since seeds of the large-lima varieties are distinctly larger and usually possess more distinct radiations from the hilum. The pitting, or dimpling, of the large lima is usually, but not always, absent in the sieva, or small, lima. The number of seeds per pod in the sieva varieties is usually 3, but many pods contain only 2 beans—rarely 1 and 4. In the large lima the usual number is 4 for the commercial varieties, but 5 and even 6 may be found, and 3 seeds are frequent and common; 2 and 1 are rare and are due usually to poor growing conditions for the plant.

#### SUMMARY AND CONCLUSION

Numerous species and varieties of lima beans recognized by botanists may be included in a single species, *Phaseolus lunatus* L. The many forms of vines, pods, and seeds found in lima beans are the result of genic, or character, differences brought about by field hybridization (due to insects) or by mutations common to this species.

Genetic evidence and cytological evidence unite to point to a single species of lima beans because artificial crosses have proved fully fertile and in all so-called "species" and forms the haploid number is 11 and the

diploid 22. The genetic inheritance of the various characters of lima beans is unchanged no matter which of the so-called "species" or formae are involved in the crosses.

While many diseases and pests found attacking lima beans attack other hosts, a number of fungus diseases and insect pests are specific in their attacks on lima beans. This is further evidence of the unity of all lima beans as one species.

Geographical distribution from the original source of the wild progenitor in the Guatemala region indicates three lines, namely: (1) the Hopi branch, extending northward in areas in the United States, (2) the Carib branch, carried to islands in the West Indies and to the Amazon basin, and (3) the Inca branch, which traveled south from the Central American point of origin to Peru. These lines of dispersal followed the trade routes of the Indians in pre-Columbian times and are identified by the characteristics of the varieties of beans included in them. Progressive improvement in size and form of the wild lima and in the quality of the bean followed the departure from the source of origin.

The dispersal of lima beans in the post-Columbian period is determined by the character of the beans identified in the established three pre-Columbian groups.

A knowledge of the origin and dispersal of the lima bean, the unity of the species, and the specificity of its diseases and pests, may be used by the plant breeder in creating useful horticultural varieties.

The concept of deCandolle of the origin of cultivated crops (recovery of a wild progenitor) and the concept of Vavilov (concentration of species and forms) agree in placing the origin of the lima bean in the Guatemala region.

The unity of all lima beans in a single species is supported by the presence of the glucoside, linamarin, the result of two enzymes imparting the characteristic lima-bean flavor found in no other bean.

The evidence presented supports Piper's contention that all lima beans belong to a single species, *Phaseolus lunatus* L.

#### ACKNOWLEDGMENTS

The collections of foreign beans studied in these investigations were made available through the agricultural plant explorers and through Professor Knowles A. Ryerson, Assistant Dean in the College of Agriculture and formerly Principal Horticulturist in Charge of Foreign Plant Introduction of the United States Department of Agriculture. Dr. J. B. McClellan, Director of the Puerto Rico Agricultural Experiment Station, and members of his staff, Dr. W. V. Cruess, of the Cali-

fornia Agricultural Experiment Station, and Mr. L. H. Churchill of the California Lima Bean Growers' Association, contributed effective coöperation in the glucoside, linamarin, studies.

Dr. F. W. McBryde, Fellow in the National Research Council, made important collections in Guatemala, and Dr. Carl O. Sauer, geographer, University of California, on the west coast of Mexico; Dr. Alfred F. Whiting, Curator of Botany of the Museum of Northern Arizona, and Dr. George T. Carter, of the San Diego State College, furnished invaluable notes and bean collections. Many others, too numerous to mention, contributed beans and services.

Assistance in the preparation of these materials was furnished by the personnel of Work Projects Administration Official Project No. 65-1-08-91-B-4.

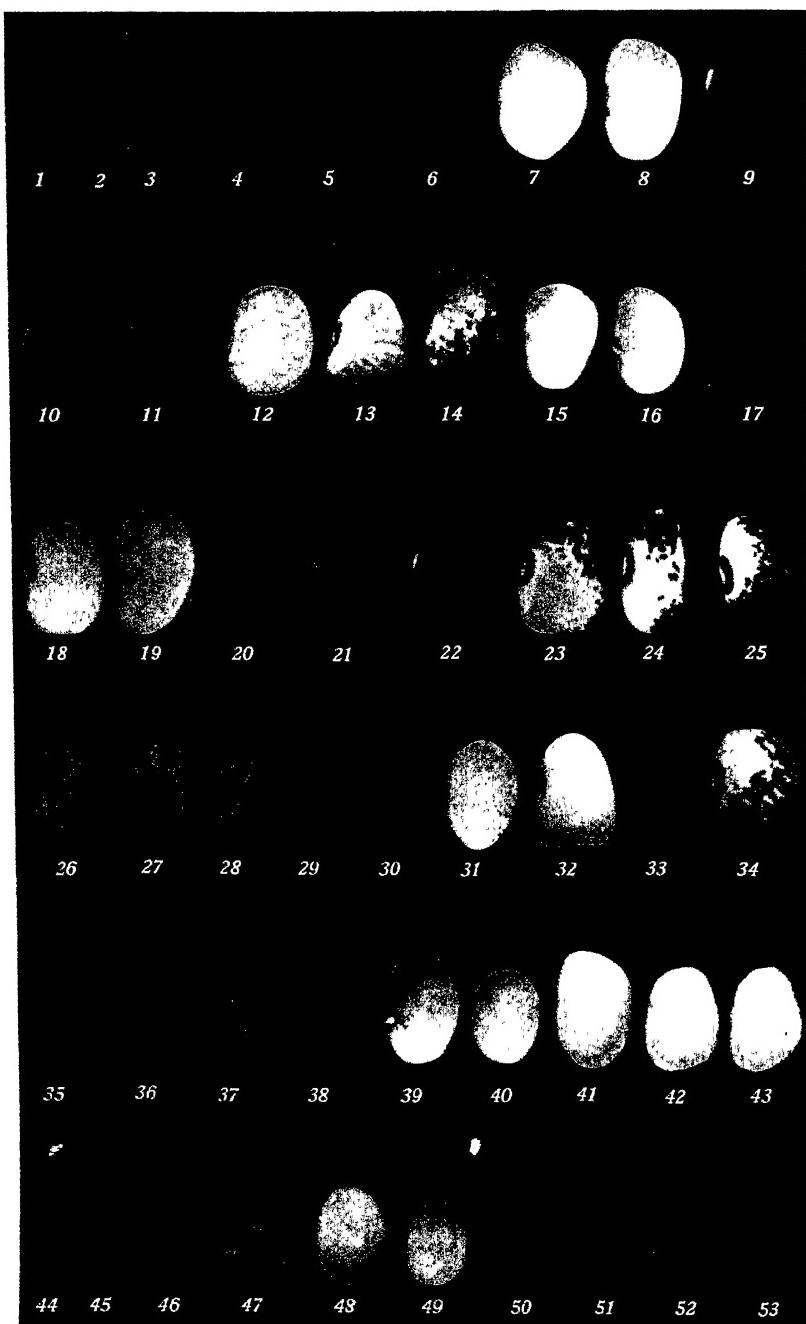
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## PLATES



## DESCRIPTION OF PLATE 1

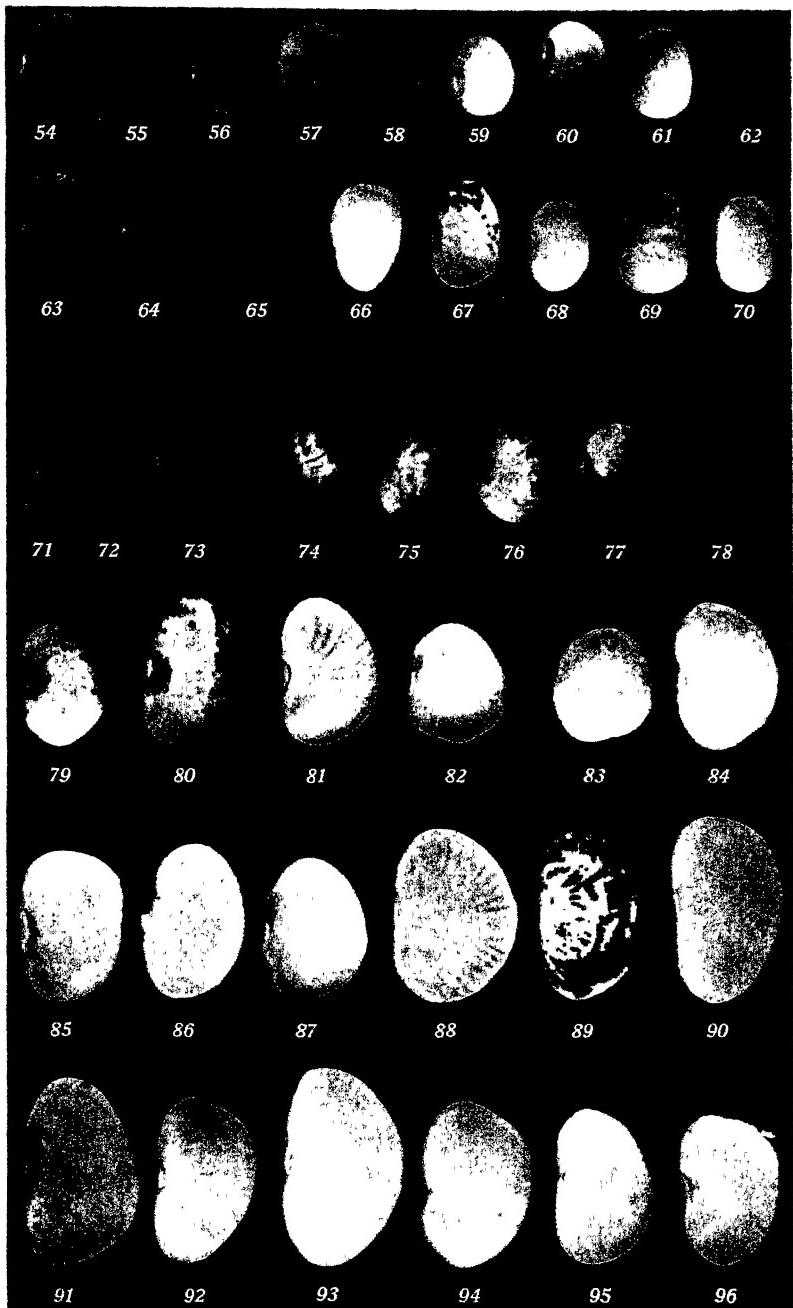
Bean no and description of seed	Grams per 100 seeds	Place collected
<b>HOPI BRANCH.</b>		
1. Indigenous, lenticular, brown mottled . . . . .	6.94	
2. Indigenous, lenticular, hilum radiations . . . . .	9.5	Guatemala
3. Brown mottled, flat . . . . .	17.5	Socorro Island, Mexico
4. Red, flecked . . . . .	76.0	
5. Black, pitted . . . . .	60.0	
6. Bush, black . . . . .	75.0	
7. Bush, white . . . . .	74.0	
8. Bush, white . . . . .	83.0	
9. Bush, red . . . . .	111.0	
10. Red . . . . .	54.3	
11. Dark red . . . . .	71.4	
12. White, dull, split seed coat . . . . .	58.6	
13. Purple star dust or white . . . . .	49.2	
14. Star dust + dark-red dorsal . . . . .	61.5	
15. White, bright . . . . .	49.0	
16. White, dull . . . . .	53.0	
17. Dark red + light-red blotches . . . . .	88.0	Hopi Reservation,
18. White, plump, sulfur dorsal . . . . .	64.0	Arizona
19. White + pale greenish . . . . .	52.4	
20. Light red + dark-red spots . . . . .	62.0	
21. Dark red + black spots . . . . .	81.4	
22. Black + brown flecks . . . . .	74.0	
23. White + star dust, black dorsal . . . . .	92.8	
24. White + star dust, dark-red dorsal . . . . .	56.8	
25. Dark red + black blotches . . . . .	44.0	
26. White + star dust + dark- and light-red striations . . . . .	85.2	
27. White + star dust + dark red . . . . .	46.6	
28. White + star dust + dark-red dorsal . . . . .	55.7	
29. Dark red + light-red blotches . . . . .	40.5	
30. Black . . . . .	46.5	
31. Willow-leaf sieva, white . . . . .	47.4	Colorado
32. Bush sieva, white . . . . .	71.5	
33. Jackson's Wonder, brown and dark-red blotches, Atlantic seacoast . . . . .	47.8	Carolina
34. Jackson's Wonder, brown and red flecks . . . . .	44.3	
35. Florida red + speckled . . . . .	77.2	Atlantic seacoast
36. Hopi brown + black striations . . . . .	61.1	
37. Hopi white + star dust + red, dorsal . . . . .	44.4	Hopi Reservation,
38. Hopi dark red + black flecks . . . . .	66.3	Arizona
39. Henderson Bush, white . . . . .	53.8	
40. Willur, vine, white . . . . .	44.0	
41. Hopi 5989, white, nematode-resistant . . . . .	56.2	California (commercial varieties)
42. Hopi 155, white, nematode-resistant . . . . .	53.6	
43. Hopi 56, white, dry-rot resistant . . . . .	47.0	

### CARIB BRANCH:

44. Indigenous, lenticular, brown mottled; same as bean no. 1 . . . . .	6.94	Guatemala
45. Indigenous, black . . . . .	13.8	
46. Brown mottled, flat; same as bean 3 . . . . .	17.5	Socorro Island, Mexico
47. Cyanide as HCN, 970 p.p.m. . . . .	45.4	
48. White + dimple . . . . .	44.0	
49. White + sulfur dorsal . . . . .	51.2	
50. Dark red . . . . .	65.9	Puerto Rico
51. Bright red + black globular . . . . .	31.7	
52. Bright red + black flecks . . . . .	42.2	
53. Dark red + black fleck, globular . . . . .	42.4	

## DESCRIPTION OF PLATE 2

Bean no. and description of seed	Grams per 100 seeds	Place collected
CARIB BRANCH ( <i>concluded</i> )		
54. Flat red + black spots . . . . .	46.2	
55. Dark red, globular . . . . .	41.1	
56. Pure brown . . . . .	45.3	
57. Brown - black flecks, globular . . . . .	44.1	
58. Brown + black flecks, globular . . . . .	30.3	
59. White, oval . . . . .	44.5	
60. White star dust + dark-red dorsal, oval . . . . .	54.5	Puerto Rico
61. White star dust + red striations, oval . . . . .	49.8	
62. Dark red + light-red flecks, globular . . . . .	34.1	
63. Flat, brown + dark-red striations . . . . .	54.8	
64. Flat, dull red + flecks . . . . .	58.4	
65. Dark red - dimple . . . . .	59.9	
66. White, plump, dimple, sulfur dorsal . . . . .	61.0	
67. White star dust + dark red . . . . .	54.8	
68. White, yellowish, oval . . . . .	44.9	Cuba
69. White, purple, star dust . . . . .	59.4	
70. White, oval . . . . .	46.5	
INCA BRANCH:		
71. Indigenous, brown mottled - black spots . . . . .	5.2	
72. Indigenous, black . . . . .	10.0	Guatemala
73. Black - flecks . . . . .	68.0	
74. Flat, star dust, yellow + black flecks . . . . .	60.0	
75. Flat, star dust, yellow + black flecks . . . . .	72.4	Canal Zone, Panama
76. White, flat, star dust + red-flecked dorsal . . . . .	70.5	
77. White, flat, star dust, bright red - black flecks . . . . .	47.3	
78. Very flat, twisted, dark red + black striations . . . . .	86.0	Guatemala
79. White, very flat, star dust, yellow and black flecks . . . . .	61.4	
80. White, very flat, black dorsal, star dust . . . . .	99.8	Canal Zone, Panama
81. White, very flat, purple, star dust, large . . . . .	81.4	
82. Fordhook, potato, bush, white . . . . .	108.8	
83. Fordhook, bush, white . . . . .	107.6	
84. Willow leaf, vine, white . . . . .	122.0	
85. Lewis, white, vine . . . . .	134.2	California (commercial varieties)
86. Dreer's Improved Bush, white . . . . .	106.9	
87. King of the Garden, pole, white . . . . .	137.6	
88. New Wonder, bush, dull white . . . . .	166.0	
89. Santa Barbara, speckled, vine . . . . .	147.6	
90. White, pale, vine . . . . .	185.9	
91. White, pale + red spot . . . . .	193.2	
92. White, pale-purple star dust . . . . .	161.0	Ica, Peru
93. White, pale . . . . .	218.4	
94. Vega, white, vine . . . . .	123.0	
95. Pacific, white, vine . . . . .	134.4	California (commercial varieties)
96. Flynn, white, vine . . . . .	116.0	



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# H I L G A R D I A

*A Journal of Agricultural Science Published by  
the California Agricultural Experiment Station*

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VOL. 15

FEBRUARY, 1943

No. 2

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## THERMODYNAMICS OF SOIL MOISTURE<sup>1</sup>

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### INTRODUCTION

THE WORKER who attempts to study the basic principles of thermodynamics with reference to soil moisture has considerable difficulty because both the nomenclature and the method of treatment in existing literature vary greatly. Writers on thermodynamics have usually had in mind specific purposes quite foreign to soil-moisture studies; their conclusions and equations, being adapted to some other particular field, are not easily applied to soil moisture. This paper aims to eliminate at least part of the difficulty and also to make certain helpful original applications. It applies the well-grounded principles of thermodynamics to a study of the soil-moisture system. The first part includes, for the convenience of the reader, some material that can be found scattered in numerous published reports and books. Such material, it is hoped, is here presented in such a way as to be more readily available.

Probably the most useful thermodynamic function, as far as the student of soil moisture is concerned, is free energy. The following treatment has been built, accordingly, around that function. The chief purpose of this paper, aside from the presentation of the basic thermodynamic principles, is to develop quantitative expressions for the dependence of the free energy of soil moisture on such factors as the adsorptive force field that surrounds a soil particle, the hydrostatic pressure on the soil moisture, the dissolved material present, and the temperature.

In mathematical treatments of physical systems, the inexperienced student cannot always distinguish clearly between the parts that result from pure mathematical manipulation and the parts that can be deduced, either directly or indirectly, from experimental measurements. Certain aspects of mathematical analysis used in this paper are difficult

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for the student of soil moisture to find elsewhere in the literature, especially in a form immediately applicable to his own research. At the beginning of this discussion are presented, therefore, several mathematical articles that do not depend on any physical or chemical facts relative to soil moisture. They are, however, used later in the paper in analyzing certain aspects of the thermodynamics of soil moisture. Since they are presented early, the reader may be more easily able to distinguish between the deductions that are purely mathematical and those that are physical. Since the mathematical developments are used only in certain parts of the treatment, the reader may well scan them over but need not necessarily master every detail before reading the general discussion that follows. He may even skip the first section entirely until he is referred back to it at some later point.

To be most useful, any treatment of thermodynamics of soil moisture must recognize certain phenomena related in some ways to plant physiology and in other ways to soil hydrodynamics. In the present treatment, three types of phenomena have been distinguished.

The first deals with the vapor pressure of soil moisture as a function of moisture content (2, 46, 104, 119, 128, 153, 154, 169).<sup>4</sup> When the soils are very wet, the vapor pressure is approximately that of free water at the same temperature. As the moisture content is decreased, the vapor pressure decreases very slightly with respect to changes in moisture content until a certain value is reached that is characteristic of the soil. At this point the decrease in the vapor pressure with respect to a decrease in moisture content becomes and remains very great. In other words, there is a moisture content where the second derivative of the vapor pressure with respect to moisture content is a maximum, which means that, at this point, the slope of the vapor-pressure-moisture-content curve changes most rapidly.

The second might be classed as a plant-physiological type of phenomenon. The extensive work of Veihmeyer, Hendrickson, and co-workers (33, 40, 73, 74, 75, 157, 158, 161, 162) has demonstrated that plants seem to grow normally (assuming other conditions to be favorable) until the moisture content is reduced to a certain value that, because of the manner in which it is defined, can be fixed only within a narrow range of moisture contents. Other work, in general, seems to support this view (15, 16, 29, 47, 152, 174). When this value is reached, the plants begin to evidence their need of water by drooping of leaves, by lack of growth, or by some other fairly obvious sign; they will no longer function normally unless water is added to the soil. According to available data (46, 153, 154), the point on the curve mentioned in the previous paragraph, where

\* Italic numbers in parentheses refer to the Bibliography at the end of this paper.

the vapor pressure of the soil moisture changes most rapidly with respect to changes in moisture content, falls in this narrow range where plants wilt. This moisture content has been characterized as the "permanent wilting percentage," and might be regarded as the lower limit above which moisture is readily available to plants. This does not mean, of course, that plants cannot dry the soil out to lower moisture contents than the permanent wilting percentage. They may continue to use some water, but at a markedly reduced rate, while their normal functioning is markedly inhibited. The permanent wilting percentage is approximately independent of the kind of plant grown in the soil, and seems to depend only upon the type of soil, being a characteristic of a given soil.

The third type of phenomenon concerns the hydrodynamics of soil moisture. If a field is saturated by irrigation or rain and then allowed to drain freely, water will at first filter through the soil rather rapidly until a certain moisture content is reached; then the drainage will practically cease (19, 20, 32, 82, 96, 97, 157, 159, 163). This moisture content is also a characteristic of the particular soil. It too is represented by a narrow range in moisture content and, when applied to field conditions, will here be called "field capacity." The "moisture equivalent" (21, 28, 87, 155, 163, 164, 165, 170, 173) is a convenient and for most soils a fairly accurate method of evaluating the field capacity. The marked slowing of the downward motion is usually reached within two or three days after a heavy rain or irrigation, the time depending on the type of soil. Any further downward movement is so slow that, from the agricultural point of view, it may be neglected. The field capacity represents the maximum amount of water that can be stored for long periods, in the absence of plants, in a soil having free drainage. This statement applies only to the soil below the depth to which evaporation is effective. Loss by evaporation is extremely small below the top 6 inches of soil (91, 157). Earlier literature (76, 97, 170), however, seemed to stress this loss.

For practical purposes in agriculture, the amount of water that is readily available to plants and that can be stored in a soil is represented by the difference in moisture content between field capacity and permanent wilting percentage. This range of what is termed "readily available water" is likewise characteristic of a given soil and nearly independent of the kind of plants grown.

After heavy irrigations amounts of water larger than field capacity can, of course, be held in the soil for short periods; but since moisture above field capacity drains out soon after application, very little of it can be used by plants. Likewise, plants can extract water to moisture contents below the permanent wilting percentage. In that case, however, they usually evidence need for water and fail to function normally.

"Field capacity" and "permanent wilting percentage," as we use these terms, are recognized by most students of soil moisture as significant in agriculture. They are not always, however, known by these names, some investigators (76, 97, 143) selecting other soil-moisture contents near these as having similar significance. These terms are either arbitrary or, like those mentioned above, less specific than one might wish; they are merely narrow ranges of moisture content. In reporting data, however, they are customarily given a specific value. This practice of reporting single values that really represent narrow ranges is sometimes misleading. The student of soil moisture bears in mind, however, that the measurement might vary by plus or minus a slight amount. For certain purposes

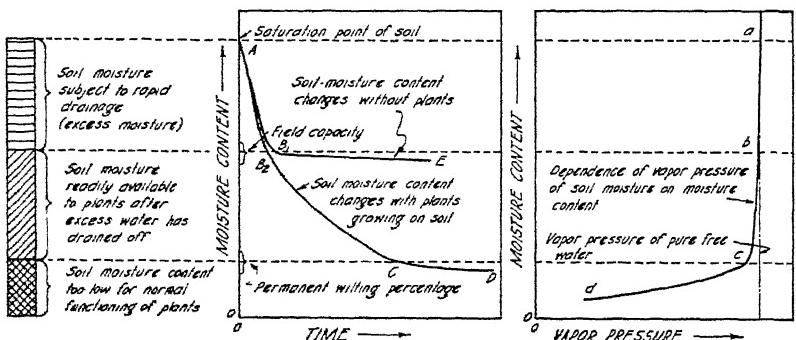


Fig. 1.—Relation between permanent wilting percentage, field capacity, range of readily available moisture, drainage, vapor pressure, and moisture content.

some investigators might find other nomenclature convenient, but for this discussion the terms mentioned above will serve.

Figure 1 summarizes graphically the three foregoing types of phenomena. It shows how the drainage, the vapor pressure, and the amount of moisture available to plants all change after a soil planted to a crop has been saturated by irrigation. It shows the relation between the field capacity, the permanent wilting percentage, and the readily available water. It also points out the nearly constant time rate of use of readily available water by a crop growing on the soil. Suppose we consider a soil immediately after irrigation in the nearly saturated state as represented by the point A. At this point the soil will possess its maximum moisture content; and the vapor pressure of its moisture will be that of free, pure water as represented by the point a. If desired, the osmotic pressure equivalent to the vapor pressure can be readily calculated from the expressions given in articles 35 and 36.

Consider first the case of a soil immediately after an irrigation with no plants growing on it. As time goes on, the soil moisture content will de-

crease very rapidly by free drainage until it reaches the point  $B_1$ , corresponding to the field capacity or the moisture equivalent. (For most agricultural soils, the moisture equivalent is nearly equal to the field capacity.) Where evaporation is unimportant, as is usually the case, the soil moisture content would remain for an indefinite period relatively constant near field capacity, as illustrated by the nearly horizontal section of the part  $B_1E$  of the curve. The vapor pressure of the soil moisture at field capacity is still practically that of free water, as given by the point  $b$ .

If, on the other hand, a crop is growing on the soil, the field capacity will be reached sooner at  $B_2$  because of transpiration. Transpiring plants will reduce the moisture content still further, eventually to the permanent wilting percentage  $C$  along some curve such as  $B_2C$ , without showing appreciable inhibition of their normal functions. At the permanent wilting percentage, the vapor pressure of the soil moisture is still relatively near that of free, pure water, as represented by the point  $c$ . With decrease of moisture content below the permanent wilting percentage, the energy required to remove the soil moisture begins to increase so rapidly and to such a high value that neither the plant nor gravity is able normally to remove much additional moisture. What little might be removed by the plant below the permanent wilting percentage is sufficient only to permit the plant to function at a greatly inhibited rate. The approximate constancy of the soil moisture content after the permanent wilting percentage is reached is represented by the almost horizontal section  $CD$ . Simultaneously the vapor pressure of the soil moisture decreases tremendously, as represented by  $cd$ . As will be shown later, the free energy of the soil moisture, being proportional to the logarithm of the vapor pressure, also begins to decrease very rapidly at the point  $c$ . These conditions and behavior are what one normally finds a few inches below the soil surface, where evaporation into the atmosphere is negligible.

The field capacity and the permanent wilting percentage may, of course, vary slightly with such factors as the temperature and the nearness of the soil moisture to the water table. The small ranges covered by the terms "field capacity" and "permanent wilting percentage" are illustrated in the diagram by the small brackets.

## MATHEMATICAL THEOREMS TO BE USED IN THE THERMO-DYNAMIC ANALYSIS OF SOIL MOISTURE<sup>5</sup>

### 1. Single-valued Functions and Perfect Differentials

Two types of functions are used in thermodynamics. The first may be represented as a single-valued function of one or more variables, as follows:

$$\phi = \phi(x, y, \dots). \quad (1)$$

A particular set of values  $(x, y, \dots)$  will represent and determine a definite state of the system and will therefore determine uniquely a single value of  $\phi$ . In consequence any infinitesimal change in  $\phi$ , which we shall represent by  $d\phi$ , depends solely upon the initial and final state or the initial and final sets of values of  $(x, y, \dots)$ . For example, the change  $d\phi$  caused by changing  $(x, y, \dots)$  to  $(x + dx, y + dy, \dots)$ , which means that  $\phi(x, y, \dots)$  becomes  $\phi(x + dx, y + dy, \dots)$ , may be expressed as follows:

$$d\phi = \phi(x + dx, y + dy, \dots) - \phi(x, y, \dots). \quad (2)$$

Assuming that the partial derivatives

$$\frac{\partial \phi}{\partial x}, \frac{\partial \phi}{\partial y}, \dots$$

exist and are continuous in the vicinity of the point  $(x, y, \dots)$ , equation 2 may be written in terms of the differentials  $(dx, dy, \dots)$  in the form

$$d\phi = \frac{\partial \phi(x, y, \dots)}{\partial x} dx + \frac{\partial \phi(x, y, \dots)}{\partial y} dy + \dots \quad (3)$$

Purely as a mathematical consequence, therefore,  $d\phi$  may be expressed as above in terms of the changes  $(dx, dy, \dots)$  in the variables  $(x, y, \dots)$  representing the state of the system. If  $\phi$  is a function of but one variable,  $x$ , we have the following almost trivial case:

$$\begin{aligned}\phi &= \phi(x), \\ d\phi &= \phi(x + dx) - \phi(x),\end{aligned}$$

and

$$d\phi = \frac{d\phi}{dx} dx.$$

<sup>5</sup> This section contains a number of mathematical articles that do not depend on any physical or chemical facts relative to soil moisture. They are, however, used later in the paper in analyzing certain aspects of the thermodynamics of soil moisture. The reader may well scan them over and then revert to them only as the occasion demands.

When the differential  $d\phi$  of a function may be represented in terms of the differentials of its dependent variables (eq. 3), we say that  $d\phi$  is a "perfect differential." For example, the independent variables  $x$  and  $y$  may represent the temperature  $T$  and specific volume  $v$ , respectively; the dependent variable  $\phi$ , the internal energy  $e$  of the system. Other properties of a function that may be represented as a perfect differential will be found in succeeding articles.

The other type of function, which we shall, for generality, here represent by  $\theta$ , is not a single-valued function of the variables of state ( $x, y, \dots$ )

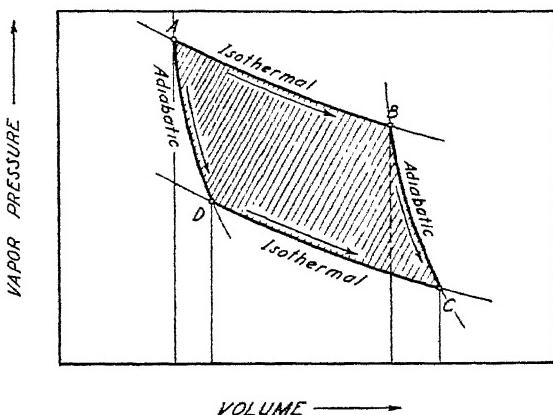


Fig. 2.—Carnot cycle for an ideal gas engine.

and cannot be represented in the form of equation 1. Instead, its values depend solely on the path followed by the process causing the change of state. Thus a change  $d\theta$  in  $\theta$  caused by going from one state to another depends not upon the initial and final values of the variables of state ( $x, y, \dots$ ), but solely on the path followed in going between the two states. Consequently, the differential  $d\theta$  can never be represented in the differential form of equation 3 above; that is, it is not a perfect differential. As an illustration from thermodynamics of such functions as these, we have the heat energy  $q$  added to the system, and the work  $w$  done by the system, whose differentials depend not upon the initial and final states of the system, but rather upon the path followed during the thermodynamic process. Consider, for example, figure 2, which represents the Carnot cycle of an ideal gas engine. The work done by the system  $dw$  on its surroundings in going from  $A$  to  $C$  along the path  $ABC$  is greater than along the path  $ADC$  by the area  $ABCD$  of the figure, although the initial and final points  $A$  and  $C$  are the same. Likewise, the heat added to the system  $dq$  in going from the state  $A$  to the state  $C$  depends upon the

path taken and not upon the initial and final states *A* and *C*. More heat is taken in by the system in going along the path *ABC* than along the path *ADC*. We therefore distinguish thermodynamic functions as to whether their differentials are perfect or not.

To fix our ideas and to bring out the meaning and importance in thermodynamics of the functions of the former type, let us consider some of the more common single-valued thermodynamic functions with which we shall be dealing.

Such variables as the temperature *T*, the pressure *P*, and the specific volume *v* serve to define the state of a system and correspond to the variables (*x*, *y*, . . .) used previously. For simple substances such as water, any two of these variables will, in general, define the state. If, for example, the pressure *P* and temperature *T* are given, the volume *v* of the water is immediately fixed. If, on the other hand, we have a simple solution composed of a solvent and solute, three variables will define the state of the system; and, in this case, they might be *P*, *T*, and the mol fraction *X* of solute. To define the state of a more complicated system, more than three variables will, of course, be necessary.

Expressed in terms of the variables of state given above are a number of thermodynamic functions such as the internal energy *e*, the heat content *h*, the free energy *f*, the maximum work *a*, and the entropy *s*.

The internal energy *e*, by the very nature of its definition, must depend on the variables of state, for it represents the internal energy of the substance, which is due to such factors as molecular attraction, kinetic energy, molecular vibration, and intramolecular and intra-atomic attraction. Experience has shown that these forms of energy are fixed by any two of the variables: specific volume, pressure, or temperature. The internal energy of water, for example, is immediately fixed when its specific volume and temperature have been given. The entropy *s* is likewise determined by the specific volume and temperature, as will be shown later. Evidently, therefore, the differentials of the internal energy *e* and the entropy *s* are perfect, since the functions *e* and *s* may be expressed in terms of the variables of state, *T*, *P*, and *v*.

The other three thermodynamic functions, whose meaning is considered in detail later in this paper, are there shown to be defined by the following equations:

$$\left. \begin{aligned} h &= e + Pv \\ f &= h - Ts = e - Ts + Pv \\ a &= e - Ts \end{aligned} \right\} (4)$$

The differentials of such functions as *h*, *f*, and *a* above are called "perfect differentials" because, as equations 4 show, the functions are com-

pletely determined by the variables of state such as  $T$ ,  $P$ , and  $v$ ; it has already been pointed out that the internal energy  $e$  and the entropy  $s$  may be expressed in terms of these same variables of state. Thus the right-hand side of equations 4 is composed of quantities which either are or can be expressed in terms of the variables of state  $T$ ,  $P$ , and  $v$ . For example, if  $T$ ,  $P$ , and  $v$  are given,  $h$  is fixed. Thus equations 4 are each perfectly analogous to equation 1 and have all the same mathematical properties. In analogy to equation 3, for instance, we have the following perfect differentials, which we shall merely accept for the present but which are derived in articles 11, 21, and 44:

$$\left. \begin{aligned} dh &= Tds + vdP \\ df &= -sdT + vdP \\ da &= -sdT - Pdv \\ de &= Tds - Pdv \end{aligned} \right\} (5)$$

The last equation follows immediately from a combination of the First and Second laws of thermodynamics, since the First Law (art. 11) states that  $de = dq - Pdv$ , where  $dq$  is the amount of heat added to the system; and the Second Law (art. 14) states that  $ds = \frac{dq}{T}$ .

## 2. The Interrelations of the Properties of a Substance

Several properties or quantities, such as  $P$ ,  $v$ ,  $T$ ,  $s$ , and  $h$ , serve to describe the state of a substance or system. Offhand, therefore, it would seem that many of these quantities would have to be known before the state of a system could be fixed and described quantitatively. Generally, however, as previously stated, any two of such quantities as those given above will quantitatively describe and uniquely fix the state of a simple substance such as water. Such descriptive quantities are usually so interrelated that to determine any two of them will for a simple substance immediately fix the others. The state of free, pure water, for example, is immediately fixed if any two of the quantities named above are known. If both the pressure and the temperature are given, the water can exist in but one state; and therefore all its other properties, such as its specific volume  $v$ , its entropy  $s$ , and its heat content  $h$ , are simultaneously fixed.

In mathematical language we speak of such a system as having two degrees of freedom or two independent variables, because two variables are needed to fix the state of the system. All the other quantities, properties, or variables of the system are then called dependent variables because their value depends on the independent variables. If, for example, the pressure and temperature of water are given, the volume, which is then the dependent variable, is immediately fixed. It is usually imma-

terial, except for convenience, which variables are taken as independent. Those remaining then become the dependent variables.

If we take  $T$  and  $P$  as the independent variables of state for water, with  $v$ , the specific volume, as the dependent variable of state, we have  $v = f(P, T)$ , which expresses the specific volume as a single-valued function of the variables of state  $T$  and  $P$ . To fix our ideas for the present, we might assume that we are dealing with water vapor, the specific volume of which will be determined by the pressure and temperature. Then from the general theorem of mathematics, stated at the beginning of article 1, we should have

$$dv = \left( \frac{\partial v}{\partial T} \right)_P dt + \left( \frac{\partial v}{\partial P} \right)_T dP.$$

If, instead,  $P$  and  $s$  had been taken as independent variables, then  $v = f(P, s)$ ; and we should have

$$dv = \left( \frac{\partial v}{\partial s} \right)_P ds + \left( \frac{\partial v}{\partial P} \right)_s dP.$$

It will be noticed that  $\left( \frac{\partial v}{\partial P} \right)$  is not the same in the two equations:  $\left( \frac{\partial v}{\partial P} \right)_T$  refers to the variation of  $v$  with respect to  $P$  with  $T$  constant, whereas  $\left( \frac{\partial v}{\partial P} \right)_s$  refers to the variation of  $v$  with respect to  $P$  with the entropy  $s$  kept constant. When the differential of the dependent variable of a function can be expressed in a form such as  $dv$  above, in terms of the differentials of the independent variables,  $dv$  is called a "perfect differential." This fact leads us to an important mathematical theorem in thermodynamics presented in article 3.

### 3. Properties of Single-valued Functions of Two Variables

Single-valued functions of but two independent variables have an important mathematical property, arising from the fact that the function may be expressed as a perfect differential. Suppose

$$d\phi = Xdx + Ydy, \quad (6)$$

where  $\phi$  is a function of  $x$  and  $y$ —that is,  $\phi = \phi(x, y)$ —and likewise where  $X$  and  $Y$  are each functions of both  $x$  and  $y$ . We shall now show that

$$\left( \frac{\partial X}{\partial y} \right)_x = \left( \frac{\partial Y}{\partial x} \right)_y.$$

To prove this theorem, consider the single-valued function  $\phi = \phi(x, y)$ . According to equation 3, we may express  $d\phi$  in the form of a total differential as follows:

$$d\phi = \left[ \frac{\partial \phi(x, y)}{\partial x} \right]_y dx + \left[ \frac{\partial \phi(x, y)}{\partial y} \right]_x dy. \quad (7)$$

Comparing equation 6 with 7, we have

$$X = \left[ \frac{\partial \phi(x, y)}{\partial x} \right]_y \text{ and } Y = \left[ \frac{\partial \phi(x, y)}{\partial y} \right]_x. \quad (8)$$

Differentiating equations 8, we get

$$\left( \frac{\partial X}{\partial y} \right)_x = \frac{\partial^2 \phi(x, y)}{\partial y \partial x} \text{ and } \left( \frac{\partial Y}{\partial x} \right)_y = \frac{\partial^2 \phi(x, y)}{\partial x \partial y}. \quad (9)$$

Since the order of differentiation is immaterial, the right-hand sides of equations 9 are equal. We conclude, therefore, from 9 that when  $d\phi = Xdx + Ydy$ , it follows that

$$\left( \frac{\partial X}{\partial y} \right)_x = \left( \frac{\partial Y}{\partial x} \right)_y. \quad (10)$$

An application of equation 10 to each of the four perfect differentials of equations 5 gives the four following, which are often referred to as Maxwell's equations:

$$\left( \frac{\partial T}{\partial P} \right)_s = \left( \frac{\partial v}{\partial s} \right)_P \quad (11)$$

$$\left( \frac{\partial s}{\partial P} \right)_T = - \left( \frac{\partial v}{\partial T} \right)_P \quad (12)$$

$$\left( \frac{\partial s}{\partial v} \right)_T = \left( \frac{\partial P}{\partial T} \right)_s, \quad , \quad (13)$$

$$\left( \frac{\partial T}{\partial v} \right)_s = - \left( \frac{\partial P}{\partial s} \right)_v \quad (14)$$

To illustrate the usefulness of these equations, let us show that the Clausius-Clapeyron equation (given by eq. 15 and considered in detail in art. 27) falls immediately out of equation 13, the third of Maxwell's equations above. From article 19 we have, by definition (eq. 70),

$$\Delta s = \frac{\Delta q}{T} = \frac{l}{T},$$

Dividing through by an increment in the volume while the temperature  $T$  remains constant, we have to a first approximation

$$\left(\frac{\partial s}{\partial v}\right)_T = \frac{l}{T} \frac{1}{\Delta v},$$

and therefore, since the left-hand side of this is equal to the left-hand side of equation 13, we obtain

$$\frac{dP}{dT} = \frac{l}{T \Delta v}. \quad (15)$$

The restriction of the constancy of volume may be omitted because the equilibrium pressure is independent of the volume. This is the Clausius-Clapeyron equation showing the relation between changes of temperature and pressure if two phases are to remain in equilibrium. Here  $l$  is the latent heat of transformation and  $\Delta v$  is the change in volume per gram (when the c.g.s. system is used) when one phase is transformed into the other.

As an application of the second of Maxwell's equations, let us derive the relation

$$\Delta s = - \int_{P_A}^{P_B} \left(\frac{\partial v}{\partial T}\right)_P dP,$$

which is used in article 77. As will be recalled, by applying equation 10 to the second of equations 5, we obtain equation 12, which is

$$\left(\frac{\partial s}{\partial P}\right)_T = - \left(\frac{\partial v}{\partial T}\right)_P.$$

That is, a change  $ds$  when  $T$  is kept constant is given by

$$ds = - \left(\frac{\partial v}{\partial T}\right)_P dP,$$

which when integrated between the limits  $P_A$  and  $P_B$  gives

$$\Delta s = s_B - s_A = - \int_{P_A}^{P_B} \left(\frac{\partial v}{\partial T}\right)_P dP. \quad (16)$$

#### 4. Simplest Conditions for the Maximum or Minimum of a Function of Any Number of Variables without Constraining Conditions

Let us consider first the simplest case where the function  $\phi$  is a function of but one variable,  $x$ . That is,

$$\phi = \phi(x).$$

At any maximum or minimum,  $x = x_0$  of  $\phi$ , the first derivative of  $\phi$  must be zero. In other words, when  $\phi$  is a maximum or minimum at  $x = x_0$ , we have

$$\left(\frac{d\phi}{dx}\right)_{x=x_0} = 0. \quad (17)$$

That is, a slight change of  $x$  in either direction from  $x = x_0$  will cause no change in  $\phi$  except for infinitesimals of higher order than the first. That is,  $\delta\phi = 0$  for infinitesimal variations  $\delta x$  about the point  $x = x_0$ , where  $x_0$  corresponds to either a maximum or minimum value of  $\phi$ . This is clarified

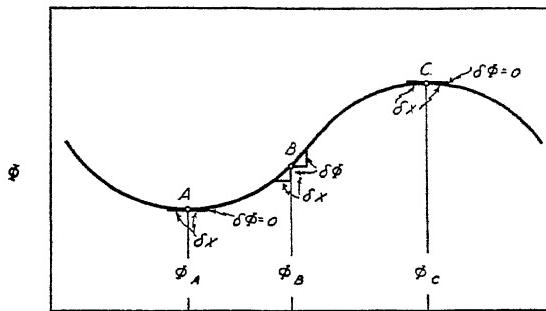


Fig. 3.—Properties of a function at a maximum and at a minimum.

by figure 3. Any infinitesimal variation  $\delta x$  in the neighborhood of either  $A$  or  $C$ , the minimum and maximum of  $\phi$ , is seen to produce no variation  $\delta\phi$  in the function  $\phi$ ; that is,  $\delta\phi = 0$  for infinitesimal variations  $\delta x$  about the point  $x = x_0$ , which corresponds to either a maximum or a minimum of the function  $\phi$ . If, however, we focus attention on  $B$ , any other point of the curve, we note that slight variations  $\delta x$  do produce appreciable variations  $\delta\phi$  of the function  $\phi$ .

Considerations of the maximum or minimum of functions of any number of variables resemble those above. Let

$$\phi = \phi(x, y, \dots).$$

Then from article 1 it follows that the differential of  $\phi$  may be represented as

$$\delta\phi = \frac{\partial\phi}{\partial x} \delta x + \frac{\partial\phi}{\partial y} \delta y + \dots \quad (18)$$

Now if the set of values  $(x_0, y_0, \dots)$  are such that  $\phi = \phi(x_0, y_0, \dots)$  is either a maximum or minimum, then any slight variation  $(\delta x, \delta y, \dots)$

of any or all the values  $(x, y, \dots)$  about the set of values  $(x_0, y_0, \dots)$  will cause no change in the function  $\phi$  except for infinitesimals of higher order than the first. That is,  $\delta\phi = 0$  for infinitesimal variations  $(\delta x, \delta y, \dots)$  about the set of values  $(x_0, y_0, \dots)$ , which corresponds to either a maximum or minimum of the functions  $\phi$ . Obviously,  $\delta\phi$  must equal zero for variations  $(\delta x, \delta y, \dots)$  about  $(x_0, y_0, \dots)$ , for if the variations  $(\delta x, \delta y, \dots)$  produced a change  $\delta\phi$  different from zero, the set of values  $(x_0, y_0, \dots)$  could not correspond to a maximum or minimum of  $\phi$ .

Further, since  $\delta\phi$  must equal zero for any arbitrary set of variations  $(\delta x, \delta y, \dots)$  about  $(x_0, y_0, \dots)$ , according to equation 18 we must have

$$\frac{\partial\phi}{\partial x} = 0, \quad \frac{\partial\phi}{\partial y} = 0, \dots \quad (19)$$

in perfect analogy with equation 17. This follows because if any one of the partial derivatives—for example,  $\frac{\partial\phi}{\partial x}$ —were not equal to zero at  $(x_0, y_0, \dots)$ , then  $\phi(x, y_0, z_0, \dots)$ , which is a function of  $x$  alone, would be either increasing as  $x$  passes through the value  $x_0$ , or else decreasing, according to the sign of  $\frac{\partial\phi}{\partial x}$ . In neither case, therefore, could  $\phi(x, y, \dots)$  have a maximum or a minimum at  $(x_0, y_0, \dots)$ .

That the conditions in equations 19 must hold also follows from the fact that if any of the partial derivatives were not equal to zero, the variations  $(\delta x, \delta y, \dots)$  could not be carried out in any arbitrary manner but would have to be always so adjusted that  $\delta\phi = 0$  in equation 18. There are no restrictions on the variations, for they are independent of each other. As will be remembered, the variations  $(\delta x, \delta y, \dots)$  are independent and may be carried out in any arbitrary manner about  $(x_0, y_0, \dots)$ , still keeping  $\delta\phi = 0$ , if  $(x_0, y_0, \dots)$  is to correspond to a maximum or a minimum value of  $\phi$ .

If, on the other hand,  $\delta\phi = 0$  and equations 19 are not satisfied, then  $\phi$  is merely a constant. This means that the variations  $(\delta x, \delta y, \dots)$  must take place in such a way as to leave the value of  $\phi$  unchanged. Under these conditions the variations cannot be made in an arbitrary manner, as we found to be the case above, at a maximum or minimum. This latter case can be stated mathematically from equation 18 by

$$\delta\phi = 0 = \frac{\partial\phi}{\partial x} \delta x + \frac{\partial\phi}{\partial y} \delta y + \dots$$

when

$$\phi(x, y, \dots) = \text{constant.}$$

5. Determination of the Maximums or Minimums of a Function Subject to  
One or More Constraining Conditions  
(Lagrange's Method of Undetermined Multipliers)

In article 49 on the statistical treatment of the properties of molecules, we shall have to determine the values of the independent variables  $w_1, w_2, \dots, w_n$ , for which a certain function  $W$  has its maximum, subject to several restrictions or equations of constraint. Let us now consider the presentation and proof of a general method for making this determination.

Assume that we have a function  $H_0 = H_0(w_1, w_2, \dots, w_n)$  of the  $n$  variables  $w_1, w_2, \dots, w_n$  and that we wish to find the values of  $w_1, w_2, \dots, w_n$  for which  $H_0 = H_0(w_1, w_2, \dots, w_n)$  has a maximum or minimum value subject to  $h$  conditions, restrictions, or constraints. In applying the results of this article to the specific problem of article 49, we shall there set  $H = W$ . The  $h$  conditions, restrictions, or constraints, which are also to be functions of the  $n$  variables, may be denoted by

$$\left. \begin{aligned} H_1 &= H_1(w_1, w_2, \dots, w_n) \\ &\cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \\ H_h &= H_h(w_1, w_2, \dots, w_n) \end{aligned} \right\} \quad (20)$$

Our  $h$  conditions will then be described by  $h$  fixed values  $H_1, H_2, \dots, H_h$ , although the variables  $w_1, w_2, \dots, w_n$  may vary widely. Thus, we wish to find for what values of the variables  $w_1, w_2, \dots, w_n$  the function  $H_0$  has a maximum subject to the  $h$  restrictions or conditions  $H_1, H_2, \dots, H_h$ , each of which has a fixed or assigned value.

Having stated our problem, let us now recall from article 4 an important property of a function—namely, that when  $H_0 = H_0(w_1, w_2, \dots, w_n)$ , for example, is at its maximum or minimum value, we can make small changes in the variables  $w_1, w_2, \dots, w_n$  without altering the value of  $H_0$ . In general, according to article 1, we have

$$\delta H_0 = \frac{\partial H_0}{\partial w_1} \delta w_1 + \frac{\partial H_0}{\partial w_2} \delta w_2 + \dots + \frac{\partial H_0}{\partial w_n} \delta w_n.$$

When  $H_0$  has a maximum value, we can carry out small changes,  $\delta w_1, \delta w_2, \dots, \delta w_n$ , quite independently of each other without altering  $H_0$ ; that is,  $\delta H_0 = 0$ , according to article 4. Hence, if  $H_0$  is to be a maximum or a minimum, we must have

$$\delta H_0 = 0 = \frac{\partial H_0}{\partial w_1} \delta w_1 + \dots + \frac{\partial H_0}{\partial w_n} \delta w_n, \quad (21)$$

and all the variations  $\delta w_1, \dots, \delta w_n$  about the values  $w_1, w_2, \dots, w_n$  for which  $H_0$  has a maximum or minimum may be carried out quite independently of each other. This is a universal property of any function at its maximum or minimum. In other words, without any of the restrictions given by equations 20 and to be considered below, the system has  $n$  degrees of freedom.

We now also wish to state the  $h$  conditions or restrictions in differential form. Since they are each functions of the  $n$  variables, we have

$$\delta H_1 = \frac{\partial H_1}{\partial w_1} \delta w_1 + \frac{\partial H_1}{\partial w_2} \delta w_2 + \dots + \frac{\partial H_1}{\partial w_n} \delta w_n$$

.....

$$\delta H_h = \frac{\partial H_h}{\partial w_1} \delta w_1 + \frac{\partial H_h}{\partial w_2} \delta w_2 + \dots + \frac{\partial H_h}{\partial w_n} \delta w_n.$$

Our conditions, it will be recalled, are that  $H_1, H_2, \dots, H_h$  are to remain constant no matter how the  $n$  variables change; that is, the variations  $\delta H_1, \delta H_2, \dots, \delta H_h$  are to remain zero no matter how the  $n$  variations  $\delta w_1, \delta w_2, \dots, \delta w_n$  behave. Our  $h$  conditions in differential form above, therefore, become

$$\left. \begin{aligned} \delta H_1 = 0 &= \frac{\partial H_1}{\partial w_1} \delta w_1 + \dots + \frac{\partial H_1}{\partial w_n} \delta w_n \\ &\dots \\ \delta H_k = 0 &= \frac{\partial H_k}{\partial w_1} \delta w_1 + \dots + \frac{\partial H_k}{\partial w_n} \delta w_n \end{aligned} \right\} (22)$$

Each of these  $h$  equations restricts the freedom of the system and reduces the total number  $n$  of the degrees of freedom of the system by one. Hence, with these  $h$  equations, the number of degrees of freedom (or independent variables) of the system is reduced from  $n$  to  $(n - h)$ .

Thus our problem finally resolves itself into finding the values  $w_1, w_2, \dots, w_n$  which will make  $\delta H_0$  equal zero, subject to the  $h$  conditions,  $\delta H_1 = 0, \delta H_2 = 0, \dots, \delta H_h = 0$ . Therefore the system has only  $(n - h)$  degrees of freedom. That is,  $(n - h)$  of the  $n$  variables may be varied independently of each other. We shall now proceed to solve the problem by using undetermined multipliers in accordance with Lagrange's method. Let us multiply each of equations 22 through by a different multiplier, and group them with equation 21 as follows:

$$\begin{aligned}
 & \frac{\partial H_0}{\partial w_1} \delta w_1 + \frac{\partial H_0}{\partial w_2} \delta w_2 + \dots \dots \dots + \frac{\partial H_0}{\partial w_n} \delta w_n = 0 \\
 & \lambda_1 \frac{\partial H_1}{\partial w_1} \delta w_1 + \lambda_1 \frac{\partial H_1}{\partial w_2} \delta w_2 + \dots \dots \dots + \lambda_1 \frac{\partial H_1}{\partial w_n} \delta w_n = 0 \\
 & \lambda_2 \frac{\partial H_2}{\partial w_1} \delta w_1 + \lambda_2 \frac{\partial H_2}{\partial w_2} \delta w_2 + \dots \dots \dots + \lambda_2 \frac{\partial H_2}{\partial w_n} \delta w_n = 0 \\
 & \dots \dots \dots \\
 & \lambda_h \frac{\partial H_h}{\partial w_1} \delta w_1 + \lambda_h \frac{\partial H_h}{\partial w_2} \delta w_2 + \dots \dots \dots + \lambda_h \frac{\partial H_h}{\partial w_n} \delta w_n = 0
 \end{aligned} \tag{23}$$

Since each term in a given equation is multiplied by the same constant, the equations must still remain satisfied. The  $h$  quantities  $\lambda_1, \lambda_2, \dots, \lambda_h$  are called Lagrangian multipliers; their values will be determined later. Suppose now we add all these equations 23 together, collecting terms having like coefficients of the variations  $\delta w$ —that is, all terms in the same vertical columns. We then have

$$\begin{aligned}
 & \left( \frac{\partial H_0}{\partial w_1} + \lambda_1 \frac{\partial H_1}{\partial w_1} + \lambda_2 \frac{\partial H_2}{\partial w_1} + \dots + \lambda_h \frac{\partial H_h}{\partial w_1} \right) \delta w_1 \\
 & + \left( \frac{\partial H_0}{\partial w_2} + \lambda_1 \frac{\partial H_1}{\partial w_2} + \lambda_2 \frac{\partial H_2}{\partial w_2} + \dots + \lambda_h \frac{\partial H_h}{\partial w_2} \right) \delta w_2 \\
 & + \dots \\
 & + \dots \\
 & + \left( \frac{\partial H_0}{\partial w_n} + \lambda_1 \frac{\partial H_1}{\partial w_n} + \lambda_2 \frac{\partial H_2}{\partial w_n} + \dots + \lambda_h \frac{\partial H_h}{\partial w_n} \right) \delta w_n = 0. \quad (24)
 \end{aligned}$$

It will be noticed that this equation contains  $h$  new variables  $\lambda_1, \lambda_2, \dots, \lambda_h$ .

We shall next see that by introducing the  $h$  variables or multipliers, we may change all the  $n$  variations  $\delta w_1, \dots, \delta w_n$  of equation 24 independently of each other, while the right side of the equation still remains zero. This will mean that the coefficients of all the variations must be equal to zero at all times.

As will be recalled, there are  $h$  equations of constraint (see equations 20) and therefore  $h$  dependent variables. Let these be  $w_1, w_2, \dots, w_h$ . Each of the variations  $\delta w_1, \delta w_2, \dots, \delta w_h$  is therefore dependent for its value on all the remaining  $(n - h)$  variations  $\delta w_{h+1}, \dots, \delta w_n$ . Let us then make the coefficients of each of the  $h$  dependent variations in

equation 24 equal to zero by adjusting the values of the  $h$  undetermined multipliers of Lagrange. We then have

$$\left. \begin{aligned} \frac{\partial H_0}{\partial w_1} + \lambda_1 \frac{\partial H_1}{\partial w_1} + \lambda_2 \frac{\partial H_2}{\partial w_1} + \dots + \lambda_h \frac{\partial H_h}{\partial w_1} &= 0 \\ \frac{\partial H_0}{\partial w_2} + \lambda_1 \frac{\partial H_1}{\partial w_2} + \lambda_2 \frac{\partial H_2}{\partial w_2} + \dots + \lambda_h \frac{\partial H_h}{\partial w_2} &= 0 \\ \dots &\dots \\ \frac{\partial H_0}{\partial w_h} + \lambda_1 \frac{\partial H_1}{\partial w_h} + \lambda_2 \frac{\partial H_2}{\partial w_h} + \dots + \lambda_h \frac{\partial H_h}{\partial w_h} &= 0 \end{aligned} \right\} \quad (25)$$

This is possible because we have here  $h$  equations with the  $h$  unknowns  $\lambda_1, \lambda_2, \dots, \lambda_h$ , which can be readily solved for, in an actual problem, by the well-known method of determinants. Thus we can make the first  $h$  terms of equation 24 drop out by properly choosing the  $h$  multipliers, so that equation 24 becomes

$$\begin{aligned} &\left( \frac{\partial H_0}{\partial w_{h+1}} + \lambda_1 \frac{\partial H_1}{\partial w_{h+1}} + \lambda_2 \frac{\partial H_2}{\partial w_{h+1}} + \dots + \lambda_h \frac{\partial H_h}{\partial w_{h+1}} \right) \delta w_{h+1} \\ &+ \left( \frac{\partial H_0}{\partial w_{h+2}} + \lambda_2 \frac{\partial H_1}{\partial w_{h+2}} + \lambda_3 \frac{\partial H_2}{\partial w_{h+2}} + \dots + \lambda_h \frac{\partial H_h}{\partial w_{h+2}} \right) \delta w_{h+2} \\ &+ \dots \\ &+ \left( \frac{\partial H_0}{\partial w_n} + \lambda_1 \frac{\partial H_1}{\partial w_n} + \lambda_2 \frac{\partial H_2}{\partial w_n} + \dots + \lambda_h \frac{\partial H_h}{\partial w_n} \right) \delta w_n = 0. \quad (26) \end{aligned}$$

Now, as previously stated,  $(n - h)$  variations are independent of each other; and each can, therefore, be varied in any arbitrary manner independently of the others. In equation 26 there happen to be exactly  $(n - h)$  variations,  $\delta w_{h+1}, \delta w_{h+2}, \dots, \delta w_n$ . Therefore, all the variations in 26 can be varied arbitrarily. Under these conditions the only possible way for the expression above to remain equal to zero at all times is for the coefficients of each variation in equation 26 also to be zero at all times. That is,

$$\left. \begin{aligned} \frac{\partial H_0}{\partial w_{h+1}} + \lambda_1 \frac{\partial H_1}{\partial w_{h+1}} + \lambda_2 \frac{\partial H_2}{\partial w_{h+1}} + \dots + \lambda_h \frac{\partial H_h}{\partial w_{h+1}} &= 0 \\ \dots &\dots \\ \frac{\partial H_0}{\partial w_n} + \lambda_1 \frac{\partial H_1}{\partial w_n} + \lambda_2 \frac{\partial H_2}{\partial w_n} + \dots + \lambda_h \frac{\partial H_h}{\partial w_n} &= 0 \end{aligned} \right\} \quad (27)$$

There are  $(n - h)$  of these equations, which, with the  $h$  equations of 25, give  $n$  equations in all. This is just sufficient to determine the values of the  $n$  variables  $w_1, w_2, \dots, w_n$  at the point where  $H_0$  has a maximum or minimum subject to the  $h$  constraining conditions  $H_1, H_2, \dots, H_h$ .

We have thus not only solved our problem but justified the method of its solution. In practice, the  $h$  equations of constraint (eqs. 20) may be used for evaluating the  $h$  multipliers  $\lambda_1, \lambda_2, \dots, \lambda_h$ . The mathematical technique involved will depend upon the particular problem at hand.

To illustrate these methods in determining maximums and minimums, let us consider the following very simple example:

Let us find the greatest value of the volume  $V = 8xyz$ , subject to the condition that the sum of the squares of the sides of the solid is equal to unity; that is,  $1 = x^2 + y^2 + z^2$ . Here by analogy,  $H_0 = V = 8xyz$ ; and we have only one constraining condition, which is  $H_1 = 1 = x^2 + y^2 + z^2$ . Applying equation 21, we have

$$dV = dH_0 = 8yz\,dx + 8xz\,dy + 8xy\,dz = 0.$$

The eight's can of course be dropped. Also applying equations 22, we have

$$dH_1 = 2x\,dx + 2y\,dy + 2z\,dz = 0.$$

The two's can of course be dropped. Multiplying the latter by  $\lambda$  and adding it to the former in accordance with equations 23, we have, corresponding to 24,

$$(yz + \lambda x)\,dx + (xz + \lambda y)\,dy + (xy + \lambda z)\,dz = 0$$

and in accordance with equations 25 plus 27

$$yz + \lambda x = 0; xz + \lambda y = 0; xy + \lambda z = 0.$$

We now wish to determine  $\lambda$  by means of the constraining condition. In this particular case, we can make the determination most easily by multiplying the three equations given above by  $x, y$ , and  $z$ , respectively:

$$xyz + \lambda x^2 = 0; xyz + \lambda y^2 = 0; xyz + \lambda z^2 = 0. \quad (28)$$

Substituting the values of  $x^2, y^2, z^2$  from equations 28 into the equation of constraint, we have

$$\lambda = -3xyz, \quad (29)$$

which, with  $H_0 = 8xyz = V$ , becomes

$$\lambda = -\frac{3V}{8}.$$

Substituting 29 into each of the equations 28 we have, subject to the constraining condition, the values of  $x, y, z$ , for which  $V$  is a maximum.

$$x = \sqrt{\frac{1}{3}}; y = \sqrt{\frac{1}{3}}; z = \sqrt{\frac{1}{3}}.$$

From this,

$$V = \frac{1}{3}\sqrt{\frac{1}{3}}.$$

This paragraph should be read principally in connection with article 49. In that article we shall wish to find the maximum of a function  $W = H_0$  subject to the two constraining conditions—namely, the constancy of the quantities  $e = H_1$  and  $N = H_2$ . We will have, therefore, in accordance with equations 21 and 22, the following:

$$\left. \begin{aligned} \delta H_0 &= \delta W = 0 = (w_1 \ln w_1) \delta w_1 + (w_2 \ln w_2) \delta w_2 + \dots + (w_n \ln w_n) \delta w_n \\ \delta H_1 &= \delta e = 0 = \epsilon_1 \delta w_1 + \epsilon_2 \delta w_2 + \dots + \epsilon_n \delta w_n \\ \delta H_2 &= \delta N = 0 = \delta w_1 + \delta w_2 + \dots + \delta w_n \end{aligned} \right\} \quad (30)$$

and

where the terms  $W$  and  $\epsilon$  have the same meaning as in article 49. In this case, for the  $i$ th term, we have

$$\frac{\partial H_0}{\partial w_i} = w_i \ln w_i, \quad \frac{\partial H_1}{\partial w_i} = \epsilon_i, \quad \text{and} \quad \frac{\partial H_2}{\partial w_i} = 1.$$

In accordance with the general solution just presented, we will introduce two multipliers, which will be called  $\alpha$  and  $\beta$  corresponding to  $\lambda_1$  and  $\lambda_2$  in the previous general treatment, and get the following  $n$  relations, one for each variable  $w_1$  to  $w_n$ :

$$\left. \begin{aligned} (w_1 \ln w_1 + \alpha \epsilon_1 + \beta) &= 0 \\ (w_2 \ln w_2 + \alpha \epsilon_2 + \beta) &= 0 \\ \dots &\dots \\ (w_n \ln w_n + \alpha \epsilon_n + \beta) &= 0 \end{aligned} \right\} \quad (31)$$

from which the values of  $w_1, w_2, \dots, w_n$ , when  $W$  has a maximum, are determined subject to the two constraining conditions,  $H_1$  and  $H_2$ .

#### 6. Relation between a Partial Differential and Its Reciprocal

Suppose variables  $x, y, z$  to be connected by an equation so that only two of the variables are independent—that is, each of the variables is a function of the other two. We wish to prove that

$$\left( \frac{\partial z}{\partial x} \right)_y = \frac{1}{\left( \frac{\partial x}{\partial z} \right)_y}.$$

To do so, let us first assume that  $x$  is a function of both  $y$  and  $z$ . According to equation 3, we must then have

$$dx = \left( \frac{\partial x}{\partial y} \right)_z dy + \left( \frac{\partial x}{\partial z} \right)_y dz.$$

If  $z$  is a function of both  $x$  and  $y$ , we have similarly

$$dz = \left( \frac{\partial z}{\partial x} \right)_y dx + \left( \frac{\partial z}{\partial y} \right)_x dy.$$

Let us assume, from here on, that  $x$  and  $y$  are to be the independent variables, and  $z$  the dependent one. If we eliminate  $dz$  of the former equation by means of the latter, we have

$$dx = \left( \frac{\partial x}{\partial y} \right)_z dy + \left( \frac{\partial x}{\partial z} \right)_y \left[ \left( \frac{\partial z}{\partial x} \right)_y dx + \left( \frac{\partial z}{\partial y} \right)_x dy \right].$$

Rearranging,

$$dx = \left[ \left( \frac{\partial x}{\partial y} \right)_z + \left( \frac{\partial x}{\partial z} \right)_y \left( \frac{\partial z}{\partial y} \right)_x \right] dy + \left( \frac{\partial x}{\partial z} \right)_y \left( \frac{\partial z}{\partial x} \right)_y dx$$

or

$$0 = \left[ \left( \frac{\partial x}{\partial y} \right)_z + \left( \frac{\partial x}{\partial z} \right)_y \left( \frac{\partial z}{\partial y} \right)_x \right] dy + \left[ \left( \frac{\partial x}{\partial z} \right)_y \left( \frac{\partial z}{\partial x} \right)_y - 1 \right] dx.$$

Since we assumed that  $x$  and  $y$  were to be the independent variables and  $z$  the dependent one,  $dx$  and  $dy$  may be varied independently of each other in any arbitrary manner. Under such a condition the only way in which this equation can remain zero at all times is for the coefficients of  $dx$  and  $dy$  to vanish for all values of  $dx$  and  $dy$ . That is, we must have

$$\left( \frac{\partial x}{\partial y} \right)_z + \left( \frac{\partial x}{\partial z} \right)_y \left( \frac{\partial z}{\partial y} \right)_x = 0,$$

which is of no immediate use, and

$$\left( \frac{\partial x}{\partial z} \right)_y \left( \frac{\partial z}{\partial x} \right)_y - 1 = 0,$$

from which

$$\left( \frac{\partial z}{\partial x} \right)_y = \frac{1}{\left( \frac{\partial x}{\partial z} \right)_y}. \quad (32)$$

We can obtain two other equations like 32 between  $x, y, z$  by assuming  $x$  and  $y$  in turn to be the dependent variables and carrying through the same process twice, as above. By cyclic permutation, however, we can write them down immediately as

$$\left( \frac{\partial x}{\partial y} \right)_z = \frac{1}{\left( \frac{\partial y}{\partial x} \right)_z} \quad \text{and} \quad \left( \frac{\partial y}{\partial z} \right)_x = \frac{1}{\left( \frac{\partial z}{\partial y} \right)_x}.$$

### 7. Another Theorem on Partial Differentiation

Suppose we have three variables such as  $x, y, z$  and suppose that  $z$  is a function of  $y$  and that  $y$  is a function of  $x$ . Also,  $x, y, z$  may each be functions of several other variables. The latter will be denoted by the symbols  $\phi_1, \phi_2, \dots$ . We want to prove that it is then possible to write

$$\left( \frac{\partial z}{\partial x} \right)_\phi = \left( \frac{\partial z}{\partial y} \right)_\phi \left( \frac{\partial y}{\partial x} \right)_\phi$$

where  $\phi$  denotes that all the variables,  $\phi_1, \phi_2, \dots$  except  $x, y, z$  remain constant.

Since  $z$  is a function of  $y$ , we have for a change  $dz$  expressed in terms of a change  $dy$ , and the others,  $d\phi_1, d\phi_2, \dots$

$$dz = \left( \frac{\partial z}{\partial y} \right) dy + \left( \frac{\partial z}{\partial \phi_1} \right) d\phi_1 + \left( \frac{\partial z}{\partial \phi_2} \right) d\phi_2 + \dots$$

We shall assume here that all the independent variables except  $y$  remain unchanged—that is,  $d\phi_1 = 0, d\phi_2 = 0, d\phi_3 = 0, \dots$ . We have then,

$$dz = \left( \frac{\partial z}{\partial y} \right)_\phi dy.$$

Similarly, since  $y$  is a function of  $x$ , we have

$$dy = \left( \frac{\partial y}{\partial x} \right)_\phi dx.$$

If we eliminate  $dy$  from the former by means of the latter, we have

$$dz = \left( \frac{\partial z}{\partial y} \right)_\phi \left( \frac{\partial y}{\partial x} \right)_\phi dx;$$

or, dividing through by  $dx$  and writing  $\left( \frac{dz}{dx} \right)$  as  $\left( \frac{\partial z}{\partial x} \right)_\phi$ , since the  $\phi$ 's remain constant during the differentiation, we find

$$\left( \frac{\partial z}{\partial x} \right)_\phi = \left( \frac{\partial z}{\partial y} \right)_\phi \left( \frac{\partial y}{\partial x} \right)_\phi. \quad (33)$$

### 8. Evaluation of Integrals to be Used in the Statistical Study of Molecules

We wish to evaluate a number of definite integrals to be used later. They are all based on the following one:

$$G = \int_0^\infty e^{-x^2} dx. \quad (34)$$

If we let  $x = au$  and consider  $a$  in this equation to be a constant, we have

$$G = \int_0^\infty e^{-a^2 u^2} adu$$

where, instead of integrating  $x$  from zero to infinity, we now integrate  $u$  from zero to infinity, since  $u = \frac{0}{a} = 0$  when  $x = 0$  and  $u = \frac{\infty}{a} = \infty$  when  $x = \infty$ .

On the other hand, since a definite integral is only a function of the limits and does not depend on the letter used to symbolize the variable, we may write quite independently of equation 34:

$$G = \int_0^\infty e^{-a^2} da.$$

Both of the two latter definite integrals have the same numerical value  $G$ , since they have the same form and have corresponding limits of integration. Multiplying the two latter equations together, we have

$$G^2 = \int_0^\infty du \int_0^\infty e^{-a^2(1+u^2)} ada$$

which with any table of integrals reduces to

$$G^2 = \int_0^\infty du \cdot \frac{1}{2(1+u^2)}$$

and by further integration becomes

$$G^2 = \frac{1}{2} \left| \tan^{-1} u \right|_0^\infty = \frac{\pi}{4}.$$

Hence we obtain our first important integral,

$$G = \frac{\sqrt{\pi}}{2} = \int_0^\infty e^{-x^2} dx. \quad (35)$$

From the above we may obtain integration of other integrals. Consider the following, where  $a$  is a constant:

$$\int_0^\infty e^{-ax^2} dx = \frac{1}{\sqrt{a}} \int_0^\infty e^{-ax^2} d(\sqrt{a}x) = \frac{1}{2} \sqrt{\frac{\pi}{a}} \quad (36)$$

where we have applied equation 35 to integrate the second integral.

In the expression

$$\int_{-\infty}^{\infty} e^{-ax^2} dx$$

the integrand is symmetrical with respect to the  $y$  axis. The positive and negative half of the integral are therefore equal. We then have

$$\int_{-\infty}^{\infty} e^{-ax^2} dx = 2 \int_0^{\infty} e^{-ax^2} dx = \sqrt{\frac{\pi}{a}}, \quad (37)$$

using 36 above.

If now we differentiate the first and last members of 36 with respect to  $a$ , we obtain

$$\int_0^{\infty} x^2 e^{-ax^2} dx = \frac{1}{4} \sqrt{\frac{\pi}{a^3}}. \quad (38)$$

Using this equation, we may immediately integrate the following. We shall find that since the integrand is symmetrical with respect to the  $y$  axis and since therefore the positive and negative half of the integrand are equal, we have

$$\int_{-\infty}^{\infty} x^2 e^{-ax^2} dx = 2 \int_0^{\infty} x^2 e^{-ax^2} dx = \frac{1}{2} \sqrt{\frac{\pi}{a^3}}. \quad (39)$$

Differentiating 39 with respect to  $a$  again, we have

$$\int_0^{\infty} x^4 e^{-ax^2} dx = \frac{3}{8} \sqrt{\frac{\pi}{a^5}} \quad (40)$$

and, since the following integral is symmetrical with respect to the  $y$  axis,

$$\int_{-\infty}^{\infty} x^4 e^{-ax^2} dx = 2 \int_0^{\infty} x^4 e^{-ax^2} dx = \frac{3}{4} \sqrt{\frac{\pi}{a^5}}. \quad (41)$$

#### 9. Determination of the Partial Specific Volume from the Specific Volume and the Mol Fraction

Let us first state the meaning of the terms to be used.

**Weight Fraction.**—If a solution contains  $n_1$  grams of one substance,  $n_2$  grams of another, and so on, then the weight fraction  $X_1$  of the first substance is defined by

$$X_1 = \frac{n_1}{n_1 + n_2 + \dots}$$

If the solution contains only one substance—that is, if we have now the pure solvent only—the value for the weight fraction becomes  $X_1 = 1$ .

*Specific Volume.*—If a solution contains  $n_1$  grams of one substance,  $n_2$  grams of another, and so on, and if  $V$  denotes the total volume of the solution, then the specific volume  $v$  of the solution is defined by

$$v = \frac{V}{n_1 + n_2 + \dots}.$$

*Partial Specific Volume.*—As above, let us suppose that a solution already contains  $n_1$  grams of one substance,  $n_2$  grams of another, and so

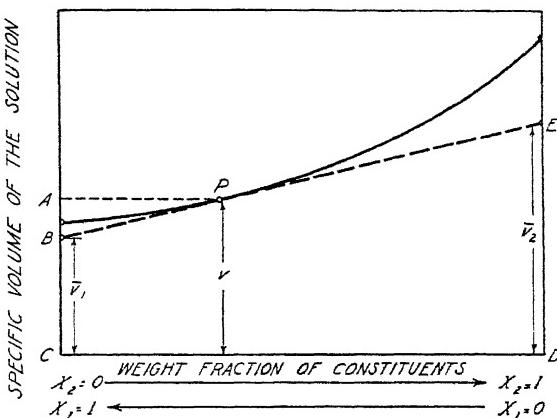


Fig. 4.—Relation of specific volume to the weight fraction of the constituents of a solution.

on, and that the total volume of the solution is  $V$ . Then the partial specific volume of the first substance, which we shall symbolize by  $\bar{v}_1$ , is defined by

$$\bar{v}_1 = \frac{\partial V}{\partial n_1}.$$

That is, if we add a small amount of the first substance to the solution, keeping constant all other variables affecting the solution, the partial specific volume  $\bar{v}_1$  is the total increase in volume of the solution per unit weight of the substance added. If the amount of the solution present is very large,  $\bar{v}_1$  is the increase in volume of the solution when 1 gram of the first substance is added.

Having disposed in a preliminary way of these definitions, let us prove a theorem: if the specific volume  $v$  of a solution is plotted against the weight fraction of the constituents as shown in figure 4, we can determine the partial specific volumes of either constituent at any desired weight fraction as follows. Suppose we wish to determine the partial

specific volumes corresponding to the solution at  $P$ . We then erect the tangent at the point  $P$ . Its intercept  $CB$  on the ordinate  $X_1 = 1$  is equal to the partial specific volume  $\bar{v}_1$  of the first constituent; its intercept  $DE$  on the ordinate  $X_2 = 1$ , to the partial specific volume  $\bar{v}_2$  of the second constituent.

The proof is mainly geometrical. The slope of the curve or (what is the same thing) the slope of the tangent, at any point  $P$ , for example, is given by  $\frac{dv}{dX_2}$ . Therefore  $AB = X_2 \frac{dv}{dX_2}$ . Consequently, we have for the segment  $AC = v$ :

$$v = \bar{v}_1 + X_2 \frac{dv}{dX_2}. \quad (42)$$

To prove this, let us recall that

$$v = \frac{V}{n_1 + n_2}.$$

If  $n_1$  is changed,

$$dv = \frac{dV}{n_1 + n_2} - \frac{V dn_1}{(n_1 + n_2)^2}. \quad (43)$$

Also

$$X_2 = \frac{n_2}{n_1 + n_2}. \quad (44)$$

Therefore

$$dX_2 = -n_2 \frac{dn_1}{(n_1 + n_2)^2}. \quad (45)$$

Dividing equation 43 by 45 and multiplying the result by equation 44, we have

$$X_2 \frac{dv}{dX_2} = -\frac{dV}{dn_1} + \frac{V}{n_1 + n_2}. \quad (46)$$

Now, from the definitions given earlier, 46 becomes

$$X_2 \frac{dv}{dX_2} = -\bar{v}_1 + v$$

and

$$v = \bar{v}_1 + X_2 \frac{dv}{dX_2},$$

which is the same as 42 and therefore proves the theorem, since exactly the same procedure would be followed in showing that the intercept  $DE$  equals the partial specific volume  $\bar{v}_2$ .

## THE THREE FUNDAMENTAL LAWS OF THERMODYNAMICS AND THEIR BASIC CONSEQUENCES

### 10. Thermodynamic Concepts

For the present, attention will be confined to a single substance, such as water, in the solid, the liquid, or the gaseous phase, and consisting of any number of coexisting phases, all parts of which are in thermal equilibrium with one another. Some of the thermodynamic quantities with which we shall deal are proportional to the mass of water considered, such as the total internal energy of the water, its volume, its total heat content, and its weight, and will be symbolized by capital letters. When these quantities are referred to unit mass of water, they will be symbolized by small letters, such as  $e$ ,  $v$ , and  $h$ . Other quantities used, which do not refer to unit mass, are the temperature  $T$ , the hydrostatic pressure  $P$ , the vapor pressure  $p$ , and the total volume  $V$ .

Since thermodynamics deals with energy and its transformations, the term "energy" must be clearly understood. Energy is the capacity of a body or system to perform work. Since the work done is a measure of the energy expended, both energy and work are measured in terms of the same unit, such as the erg. Energy stored in a system by virtue of motion, either of itself as a whole or of its parts, is known as "kinetic energy." Thus we may speak of the kinetic energy of a body of water moving through a pipe or the kinetic energy of the randomly moving molecules that make up the body of water. Energy stored in a system by virtue of the relative positions of the parts is called "potential energy." The energy contained in a body of water, for example, by virtue of its temperature and its molecular arrangement, is composed of both of the former kinds of energy. The sum of its internal kinetic and potential energies is known as its "internal energy." This includes all forms of energy due to molecular atomic and subatomic motions, as well as the potential energy of the system due to the existence of electrical and magnetic forces.

Classical thermodynamics is based entirely on the two fundamental laws that follow.

### 11. The First Law of Thermodynamics

The First Law of thermodynamics may be stated as follows: *The increase  $\Delta e$  in the internal energy of a substance, such as water, during any transformation is equal to the amount of heat  $\Delta q$  taken in, minus the work  $\Delta w$  done by the substance.* That is,

$$\Delta e = \Delta q - \Delta w$$

or

$$\Delta q = \Delta e + \Delta w.$$

Or if the only work done is that of expansion against a pressure  $P$ , we have

$$\Delta q = \Delta e + P \Delta v. \quad (49)$$

This is merely the law of conservation of energy generalized to include heat as a form of energy. Suppose, for example, we add some heat  $\Delta q$  to water vapor. This heat energy may appear partly as work  $\Delta w$  done by the vapor in changing its volume and partly as a change in its internal energy  $\Delta e$  due to a change in its temperature. The sum of the work  $\Delta w$  done by the water vapor in changing its volume and the change in its internal energy  $\Delta e$  is always equal to the amount of heat energy  $\Delta q$  added to the water vapor (eq. 48).

#### 12. Specific Heat $c$ , Internal Energy $e$ , and Heat Content $b$

*General Definition of Specific Heat.*—Suppose the temperature of 1 gram of a substance rises from  $T$  to  $T + \Delta T$  because of the intake of an amount of heat,  $\Delta q$ . Let us consider  $\frac{\Delta q}{\Delta T}$ . Then in the limit when  $\Delta T$  approaches zero, we shall define  $c$ , the specific heat of the substance, at the temperature  $T$  as equal to  $c = \frac{dq}{dT}$ .

Since the amount of heat  $dq$  required to raise the temperature of the substance by an amount  $dT$  differs with the condition under which the heat is added, we shall have a corresponding number of different specific heats. If the heat is added while the volume of the material is kept constant,  $\frac{dq}{dT}$  equals  $c_v$ , the specific heat of the substance at constant volume. If, on the other hand, the heat is added so that the pressure on the system is constant,  $\frac{dq}{dT}$  equals  $c_p$ , the specific heat of the substance at constant pressure.

Let us now consider a homogeneous body undergoing a transfer of heat  $\Delta q$  and of mechanical work  $\Delta w$  either to or from the surroundings. According to the First Law of thermodynamics, we have

$$dq = de + Pdv$$

and for the specific heat  $c$ ,

$$c = \frac{dq}{dT} = \frac{de}{dT} + P \frac{dv}{dT}. \quad (50)$$

*Specific Heat at Constant Volume*  $c_v$ .—If heat is added to the substance while its volume is kept constant,  $dv$  in equation 50 will be zero. Thus,

$$c_v = \left( \frac{de}{dT} \right)_v. \quad (51)$$

Hence  $c_v$ , the specific heat at constant volume, is equal to the rate of change of the internal energy  $de$ .

*Specific Heat at Constant Pressure*  $c_p$ .—If, on the other hand, heat is added while the pressure  $P$  on the substance is kept constant, we have (eq. 50)

$$c_p = \left( \frac{dq}{dT} \right)_P = \left( \frac{de}{dT} \right)_P + P \left( \frac{dv}{dT} \right)_P \quad (52)$$

or, since  $P$  is constant,

$$c_p = \left[ \frac{d(e + Pv)}{dT} \right]_P. \quad (53)$$

Let us introduce the following important abbreviation for the quantity in parenthesis and set:

$$h = e + Pv. \quad (54)$$

Because of its wide importance in thermodynamics, the quantity  $h$  has been given the special name "heat content." Using the heat content,  $h$ , equation 53 becomes:

$$c_p = \left( \frac{dh}{dT} \right)_P \quad (55)$$

or

$$dh = c_p dT. \quad (56)$$

Thus  $c_p$ , the specific heat at constant pressure, is equal to the rate of change of  $h$ , the heat content, with temperature; whereas, as indicated earlier,  $c_v$ , the specific heat at constant volume, is equal to the rate of change of  $e$ , the internal energy, with temperature.

Equation 56 also serves to define the heat content  $h$ , when the specific heat at constant pressure  $c_p$  is known as a function of the temperature. Since the heat content at the temperature of absolute zero is taken as zero, as shown in the consideration of the Third Law of thermodynamics (art. 20), we have

$$h_T = \int_0^T c_p dT. \quad (57)$$

Or, if we know the heat content at the temperature  $T_1$ , we may write the heat content at some other temperature  $T_2$  according to equation 57 as follows:

$$h_{T_2} = h_{T_1} + \int_{T_1}^{T_2} c_p dT. \quad (58)$$

### 13. Reversible Cycles

Throughout thermodynamics we continually deal with what is called a "thermodynamically reversible process." This is one carried out so slowly that the system is continuously in equilibrium with its surroundings, that is, with respect to temperature, pressure, or any other variables which determine its state. The process can therefore be made to proceed in the opposite direction by an infinitesimal change in any one of the conditions, such as temperature or pressure, that determine the direction of the process. If, for example, a gas is expanding reversibly, then an infinitesimal increase in the external pressure should cause the gas to contract. That is, the internal pressure differs only by an infinitesimal from the external pressure. Clearly, since the net force carrying on the reversible process is an infinitesimal, the process will be carried on with infinite slowness, so that all parts of the system remain at thermal equilibrium. Although this type of change never takes place in nature, we can make any change approach reversibility as closely as we please.

### 14. The Second Law of Thermodynamics

The Second Law of thermodynamics may be stated: *No self-acting device unaided by an external agency can transfer heat from a body of lower temperature to one of higher temperature.*

A self-acting device is one on which no work is done by an outside agency and which is so operated as to take the working substance through one or more complete cycles. After such a cycle, the final state of the working substance employed in the device is the same as at the start.

An alternative statement of the Second Law is: *Work can never be produced in a reversible cycle of changes operating in surroundings all at the same temperature.* Applying the First Law of thermodynamics to the Second, we arrive at a quantitative relation which states that when work is produced by a reversible cycle operating between two absolute temperatures  $T_1$  and  $T_2$ , where  $T_1$  is greater than  $T_2$ , the quantity of work performed spontaneously during the cycle, as will be proved later, is

$$w = q \frac{(T_1 - T_2)}{T_1},$$

*w,*

where  $q$  is the heat absorbed at the higher temperature  $T_1$ . We may arrive at this expression by considering any one of several reversible processes, among which the most common is probably the Carnot cycle, to be discussed later. Clearly, if  $T_1$  is less than  $T_2$ , then  $w$ , the work done by the process, is negative. This means that  $w$  units of work must be done on the working substance to transfer a quantity of heat from the lower temperature  $T_2$  to produce a quantity of heat  $q$  at the higher  $T_1$ . This agrees with the first statement (above) of the Second Law. The quantitative expression given above shows, likewise, that when  $T_2$  equals  $T_1$ —that is, when the surroundings are all at the same temperature— $w$  equals zero. According to this, no work can be produced spontaneously by the system composed of the working substance and the surroundings when both are at the same temperature, a finding that agrees with the alternative statement of the Second Law given above.

Although mechanical work can always be transformed into heat, the reverse process of converting heat into mechanical work is by no means always possible. The First Law merely specifies the quantitative relation that must exist between any interchange of work and heat. The Second Law specifies the conditions under which it is possible to convert heat into work. That is, the Second Law limits the First. Whereas work may always be transformed into heat according to the First Law, the reverse change (heat into work) is subject to further restrictions, according to the Second Law. The Second Law also tells us the direction in which heat will flow when two bodies of heat are brought together.

To place the Second Law of thermodynamics on a quantitative basis and therefore to enable us to predict the amount of work  $w$  obtainable from a given quantity of heat  $q$ , as well as to predict the direction in which heat will flow spontaneously when two reservoirs of heat are interconnected, it has been necessary to introduce a term called "entropy," which we shall symbolize by  $s$ . The increase in entropy of a system  $ds$  is defined by

$$ds = \frac{dq}{T},$$

where  $dq$  is the amount of heat added to the system whose temperature is  $T$ . This concept will be discussed in detail later.

## 15. Carnot Cycle and Its Utility in Deriving Important Thermodynamic Relations

*Definitions of Some Thermodynamic Terms.*—Because of their repeated use, several new terms should be defined. A "cycle" is a succession of transformations that brings the working substance back to its original state. An "isothermal" transformation is one during which the tempera-

ture remains constant. An "adiabatic" transformation is one during which heat is neither taken in nor given out. A "Carnot cycle" (fig. 5) consists of two isothermal and two adiabatic transformations. During the isothermal expansion  $AB$ , the working substance takes in heat; during the isothermal contraction  $CD$  it gives out heat. During the adiabatic transformations the pressure, volume, and temperature always change in such a way that heat flows neither in nor out of the system, although mechanical work may be performed. The efficiency  $e_f$  of a heat engine or of a system acting as an engine gives the ratio of the work  $w$  done by the system on its surroundings, to the heat  $q$  taken in when the working substance goes through a complete cycle in the engine.

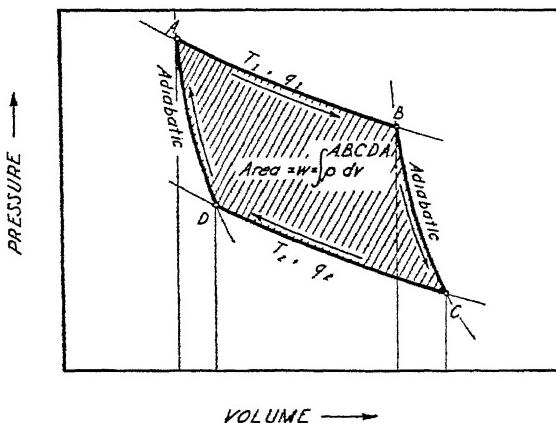


Fig. 5.—Relation of heat energy to useful work in a Carnot cycle.

*Relation between the Heat, Work, and Efficiency of a Carnot Cycle.*—The Second Law of thermodynamics and many of its implications are stated in terms of the Carnot cycle. Let us begin by determining the efficiency  $e_f$  of an engine operating in a reversible manner according to the Carnot cycle (fig. 5). We shall assume here that the working substance is a gas, though any substance may be put through a Carnot cycle. (Later in the discussion the conclusions will be applied to water vapor in equilibrium with soil moisture.) A quantity of heat  $q_1$  is taken into the system during the isothermal expansion  $AB$  at  $T_1$ , and a quantity of heat  $q_2$  is given out by the system during the isothermal contraction  $CD$  at  $T_2$ . No flow of heat  $q$  takes place during the adiabatic expansions or contractions  $BC$  and  $DA$ . The amount of work  $w$  done by the reversible engine in going through the cycle is represented by the area

$$w = \int^{(ABCDA)} P \, dv$$

enclosed by the curve. Since the gas arrives in the same condition, *A* (with respect to its internal energy) at the end of the cycle as at the beginning, we know, according to the First Law, that the  $(q_1 - q_2)$  units of heat which have disappeared from the system during the cycle are completely converted into the work *w* performed by the system or engine. Of the original amount of heat  $q_1$  given to the working substance by the surroundings, an amount  $q_1 - q_2 = w$  has been converted into work. The efficiency  $e_f$  of a reversible engine or system following a Carnot cycle is given, therefore, by

$$e_f = \frac{q_1 - q_2}{q_1} = \frac{w}{q_1}. \quad (59)$$

We specify that the process be reversible because we wish the pressure and the temperature of the working substance at all times to equal those of the surroundings with which it is in contact, except for an infinitesimal amount. Otherwise the work performed by the working substance during the isothermal expansion will be somewhat greater than the work done by the working substance on the surroundings, the discrepancy depending (as will be shown later) upon the irreversibility of the process. The part of the work performed by the system during the irreversible expansion that does not reach the surroundings is converted into heat by friction. When the process is reversible, the work *w* performed by the system or engine in passing through a complete cycle [where  $(q_1 - q_2)$  units of heat are absorbed from the surroundings] always equals the work *w* done on the surroundings.

Since the Carnot cycle is reversible, the engine may be made to run in the reverse direction *ADCBA*. In contrast to the previous case, if the cycle is carried out in the reverse direction, an amount of heat  $q_2$  is now taken from the surroundings while an amount of work *w* is done on the working substance or engine, enabling the working substance to give out to the surroundings an amount of heat  $q_1$ . In the latter case, instead of having the heat  $(q_1 - q_2)$  added to the working substance and converted into work *w* on the surroundings, we now have an amount of work *w* being performed by the surroundings on the working substance, which work is in turn converted into an amount of heat  $(q_1 - q_2)$  in the working substance; this amount of heat  $(q_1 - q_2)$  is returned to the surroundings by the completion of the cycle.

Next we shall prove two fundamental theorems of great importance, based upon the Second Law of thermodynamics.

*Theorem 1. No engine can be more efficient in converting heat into work than is the ideal Carnot engine just considered above.*

Let us assume that we have two engines working between the same

two temperatures,  $T_1$  and  $T_2$ . One, which we shall call engine  $E$ , works in a reversible cycle; the other,  $E'$ , in a cycle either reversible or irreversible. Let us also assume that  $E'$  is connected so as to drive the reversible Carnot engine  $E$ . Thus the engine or working substance  $E'$  takes in an amount of heat  $q_1'$  from the surroundings, which are at the higher temperature  $T_1$ , called the "source"; and it returns to the surroundings an amount  $q_2'$ , at the lower temperature  $T_2$  here called the "sink." The source is at  $T_1$ , a higher temperature than the sink, which is at the temperature  $T_2$ . The working substance is of course subjected to  $T_1$  and  $T_2$  at different times.

The engine  $E'$  performs an amount of work  $w'$  on  $E$  which goes simultaneously to run the reversible engine  $E$ . In consequence, the engine  $E$  takes an amount of heat  $q_2$  from the sink at the lower temperature  $T_2$  and gives out a greater amount of heat  $q_1$  to the source at the higher temperature  $T_1$ . The efficiency  $e_f'$  of the engine  $E'$  is

$$e_f' = \frac{w'}{q_1'} = \frac{q_1' - q_2'}{q_1'}. \quad (60)$$

To obtain the efficiency  $e_f$  of the reversible engine  $E$  being run by  $E'$ , let us recall that  $E$ , being a reversible engine, would take up the same amount of heat  $q_1$  from the reservoir or source at the higher temperature  $T_1$  if it were running forward (that is, in the direction  $ABCDA$ ) about the cycle as it now gives up to the source at the higher temperature  $T_1$  when running backwards (that is, in the direction  $ADCBA$ ). Also  $E$  would give up the same amount of heat  $q_2$  to the sink, if driven forwards, that it now obtains from the sink while being driven backwards by the engine  $E'$ . For the efficiency  $e_f$  of the reversible Carnot engine  $E$ , we have, therefore,

$$e_f = \frac{w}{q_1} = \frac{q_1 - q_2}{q_1}.$$

Now the work  $w'$  done by  $E'$  during each cycle equals the work  $w$  done on  $E$ , since both engines are coupled without frictional losses. Also, according to the First Law of thermodynamics (eq. 48), since the internal energy  $e$  of the working substance in the engines after the completion of a cycle is again the same as at the start, we have

$$w = q_2 - q_1$$

and

$$w' = q_2' - q_1'$$

and therefore

$$q_1 - q_2 = q_1' - q_2'. \quad (61)$$

From equations 59 and 60 in combination with 61 we have

$$e_f q_1 = e_f' q_1'. \quad (62)$$

Now we wish to show that the efficiency  $e_f'$  of the engine  $E'$  cannot be greater than the efficiency  $e_f$  of the reversible engine. To demonstrate this let us assume the converse, that  $e_f'$  is greater than  $e_f$ , and then by the method of *reductio ad absurdum* show that we are led to an inconsistency which violates the Second Law of thermodynamics.

If we assume  $e_f < e_f'$ , then from equation 62  $q_1 > q_1'$ . Therefore, from equation 61,  $q_2 > q_2'$ . As will be recalled,  $q_2'$  is the heat delivered by the engine  $E'$  to the sink at the lower temperature  $T_2$ , whereas  $q_2$  is the heat taken up from the sink at the lower temperature  $T_2$  by the reversible Carnot engine  $E$ . Therefore, since  $q_2 > q_2'$ , there is a net transfer of heat from the sink at the lower temperature  $T_2$  to the source at the higher temperature  $T_1$  when we consider the two engines  $E$  and  $E'$  coupled together as a single self-acting engine. We are thus led to a direct contradiction of the Second Law of thermodynamics when we assume that the efficiency  $e_f'$  of any engine  $E'$  is greater than the efficiency  $e_f$  of a reversible engine, for, according to the Second Law, no self-acting engine (here composed of the two engines coupled together) can transfer heat from a body of lower temperature to one of higher temperature unaided by any external agency. The efficiency  $e_f'$  of any engine must be, therefore, either equal to or less than the efficiency  $e_f$  of a Carnot engine. That is,

$$e_f' \leq e_f.$$

*Theorem 2.* Every reversible engine, no matter what its construction or working substance, has the same efficiency when working between the same two temperatures.

Suppose that  $E_1$  and  $E_2$  are two reversible engines of quite different construction whose efficiencies are  $e_{f_1}$  and  $e_{f_2}$ , when working between the same two temperatures. Since both engines are reversible, either may replace the reversible engine  $E$  of the previous discussion, the other one then replacing  $E'$  of the previous discussion. If  $E_2$  replaces  $E$  and if  $E_1$  replaces  $E'$ , we have

$$e_{f_1} \leq e_{f_2}. \quad (63)$$

If we now interchange the engines  $E_1$  and  $E_2$  so that  $E_1$  takes the place of  $E$  and  $E_2$  that of  $E'$ , we have

$$e_{f_2} \leq e_{f_1}. \quad (64)$$

Now, obviously, the inequalities 63 and 64 can be satisfied simultaneously only if

$$e_{f_2} = e_{f_1}.$$

Since  $E_1$  and  $E_2$  were any two reversible engines, each working between the temperatures  $T_1$  and  $T_2$ , then all reversible engines working between the same two temperatures have the same efficiency. Since one of these engines might be a Carnot engine, therefore every reversible engine has the same efficiency as the Carnot engine when working between the same two temperatures.

#### 16. Kelvin's Scale of Absolute Temperature

Up to now, nothing has been said about measuring temperature. If heat flows from  $T_1$  to  $T_2$  spontaneously,  $T_1$  is said to be at the higher temperature. In practice the temperature is measured by the expansion of an arbitrary substance calibrated in terms of an arbitrary temperature scale. Two fixed temperatures (such as the freezing point and the boiling point of pure water under standard conditions of pressure) are chosen on the scale, and arbitrary values are assigned to them. Having established these two fixed points, we determine other temperatures merely by the relation of the length or volume of the thermometric substance at the unknown temperature to its change in length or volume in going from one of the fixed temperatures to the other. For example, the thermometric substance often taken is mercury; and the interval between the freezing point and the boiling point of pure water is then divided into 100 equal parts by so dividing the total change in length of the mercury column. If an unknown temperature causes the mercury to expand by 15 of these equal parts, we say that the temperature has changed by 15 degrees. Though we always assume that the expansion of the thermometric substance is proportional to the temperature, this assumption is not correct, and the deviation varies from one thermometric substance to another. Thus thermometers made from such thermometric substances as mercury, alcohol, water, and nitrogen all give slightly different readings in the same constant-temperature bath except at the two fixed temperatures.

Kelvin, on the basis of reversible heat engines working in a Carnot cycle, has introduced an absolute scale of temperature entirely independent of the thermometric substance used. Suppose, for example, we consider the two fixed temperatures, one at the freezing and the other at the boiling point of pure water. The associated Carnot cycle working between these two extremes is represented in figure 6. Let us divide this Carnot cycle into 100 equal parts such that each of them has the same area on the pressure-volume diagram. We thus have 100 reversible engines, each going through a Carnot cycle. Suppose the first engine takes in heat at the boiling point of water and rejects heat to the second engine; the second takes in the heat rejected by the first and rejects heat to the third;

the third takes in heat rejected by the second and rejects heat to the fourth; and so on. The last engine will then reject heat at the temperature of freezing water. Let the temperature of the boiling water, at which the first engine takes in heat, be  $100^\circ$ ; that at which the second takes in the heat given out by the first,  $99^\circ$ ; that at which the third takes in the heat given out by the second,  $98^\circ$ ; and so on. This will give us a temperature

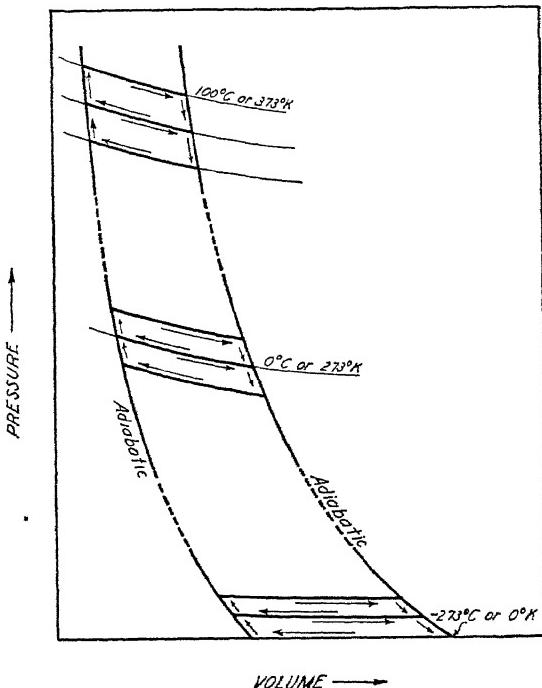


Fig. 6.—The Carnot cycle as the basis of Kelvin's scale of absolute temperature.

scale divided into 100 equal parts between the freezing and boiling points of pure water.

The 100 divisions are entirely independent of the thermometric substance used whether it be gas, mercury, alcohol, or any other substance, because (art. 15, theorem 2) the efficiency of all reversible engines working between the same temperatures is the same regardless of the working substance. No matter, therefore, what working substance is used in the set of 100 reversible engines, the temperatures they determine will always be the same. The temperature scale may in like manner be extended below and above the freezing and boiling point of pure water.

Experimental facts indicate that there is a lower temperature limit beyond which it is impossible to go. This temperature is found to be 273 of the above temperature units below the freezing point of water. At 272 units below, therefore, we should find the last reversible engine taking in heat rejected by the one above, but having no heat to reject at 273 units below. This lower limit of the temperature scale is known as the absolute zero.

Thus, as Kelvin has shown, the temperature difference between any two bodies can be measured in terms of the work performed by an ideal reversible engine working between the two temperatures, because equal temperature intervals are represented by equal areas on the pressure-volume diagram. Or—what is the same thing—equal areas on the diagram represent the performance of the same amount of mechanical work by a reversible engine. Thus in equal temperature intervals an ideal reversible heat engine performs the same amount of work per cycle. Hence the measurement of temperature on this scale is independent of the properties of any particular substance. This temperature scale is often called the "Absolute" or "Kelvin" scale. Temperatures measured on this scale (in contrast to the centigrade scale) are symbolized by the letter "A" throughout this paper. For most practical purposes, however, the divisions on the Kelvin scale can be regarded as equal in size to those on the centigrade scale.

#### 17. Relation between the Efficiency, Heat, and Temperature in an Ideal Reversible Engine

To determine the relation between the efficiency, heat, and temperature in an ideal reversible engine, let us begin by finding the relation between the area *ABEF* of figure 7 and the heat taken in during the isothermal transformation *AB*.

All points of the isothermal *FE* at  $0^\circ$  A may be considered as having zero internal energy *e*. The isothermal *FE* at  $0^\circ$  A coincides with the volume axis. This follows because in passing from one point to another on this axis, no heat is taken in or rejected by the engine or working substance, and no work is done by the engine, the pressure here being zero.

We shall now show that the area *ABEF* (fig. 7) represents the heat  $q_1$  taken in by the engine in going from *A* to *B*. Since no heat is taken in or given out by the engine in going along *AF* or *BE*, these being adiabatics, the increase in internal energy  $E_A$  of the working substance in going from *F* to *A* is equal to the work done on the working substance in going from *F* to *A*—that is, the area *AHF*. Likewise the increase in internal energy  $E_B$  of the working substance in going from *E* to *B* is equal to the work done on the working substance in going from *E* to *B* and is represented by

the area  $BKE$ . The change in internal energy ( $E_B - E_A$ ) in going from  $A$  to  $B$  is represented by the difference in areas  $BKE$  and  $AHF$ , since the working substance has the same internal energy at  $F$  and at  $E$ . Also the work done  $w$  in going from  $A$  to  $B$  is represented by the area  $ABKH$ . Now, according to the First Law, equation 48, we have

$$q_1 = w + (E_B - E_A).$$

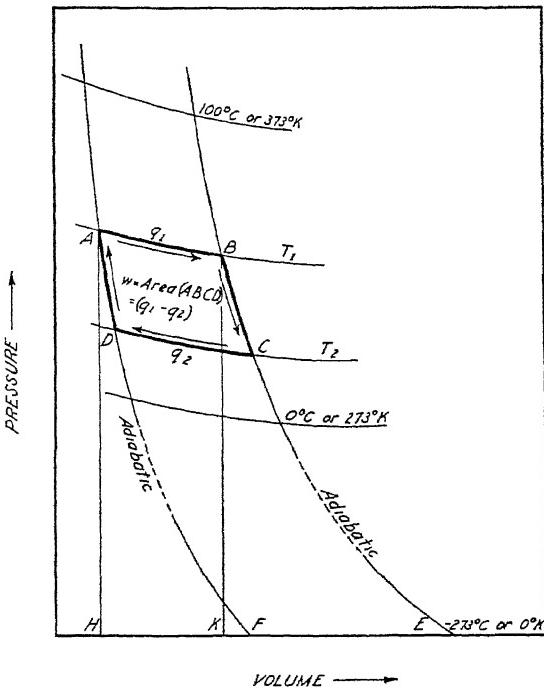


Fig. 7.—Relation between heat energy, maximum useful work, and temperature in a Carnot cycle.

Expressing this relation in terms of the areas of figure 7, we have  $q_1$  represented by the area

$$q_1 = ABKH + (BKE - AHF)$$

or

$$= ABEH - AHF = ABEF.$$

Thus the heat  $q_1$  taken in by the working substance while going from  $A$  to  $B$  is the area  $ABEF$  included between the two adiabatics. Similarly, the heat  $q_2$  taken in while going from  $D$  to  $C$  is the area  $DCEF$ .

Now we can express the total areas,  $q_1$  and  $q_2$ , between the adiabatics

in terms of the area of the small Carnot cycles considered in the previous article and in figure 6. Let  $Q$  represent the area of any one of the small cycles. Since there are  $T_1$  small cycles below the temperature  $T_1$ , the area  $ABEF$ , or  $q_1$ , equals  $T_1Q$ . Likewise  $q_2$  equals  $T_2Q$ .

Let us now calculate by equation 59 the efficiency  $e_f$ , in terms of temperature, of an ideal reversible engine operating in the Carnot cycle  $ABCD$  such that heat  $q_1$  is taken in by the working substance along  $AB$  and heat  $q_2$  is given out by the working substance to the surroundings along  $CD$ , while during the cycle an amount of work  $w$  is performed by the surroundings on the working substance. We have

$$e_f = \frac{w}{q_1} = \frac{q_1 - q_2}{q_1} = \frac{T_1Q - T_2Q}{T_1Q} = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}. \quad (65)$$

From the third and last of these members it follows that

$$\frac{q_1}{T_1} = \frac{q_2}{T_2}. \quad (66)$$

As equation 66 shows, when we are dealing with a reversible heat engine, the ratio of the amount of heat  $q_1$  (taken in by the working substance at the temperature  $T_1$ ) to the temperature  $T_1$  always equals the ratio of the amount of heat  $q_2$  (given out by the working substance at the lower temperature  $T_2$ ) to the temperature  $T_2$ .

In the previous discussion no formal convention was made as to the signs of the  $q$ 's. The expressions arrived at are in the same form as in most treatises on thermodynamics. Equation 66 may obviously be written in the following forms:

$$\frac{q_1}{T_1} - \frac{q_2}{T_2} = \frac{q_1}{T_1} + \frac{(-q_2)}{T_2} = 0. \quad (67)$$

Equation 67 shows that, in any reversible Carnot cycle, the heat taken in by a system divided by the temperature at which it is taken in, minus the heat given out by the system divided by the temperature at which it is given out, is zero.

#### 18. Relation between the Energy Available for Mechanical Work and the Temperature in Any Reversible Process

For any ideal heat engine operating in a reversible cycle between the temperatures  $T_1$  and  $T_2$ , the maximum amount of work obtainable during the cycle is shown by equation 65, to be

$$w = \frac{q_1(T_1 - T_2)}{T_1} = q_1 - q_1 \frac{T_2}{T_1}. \quad (68)$$

The maximum efficiency, therefore, of an engine operating between the temperatures  $T_1$  and  $T_2$  is

$$e_f = \frac{w}{q_1} = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1} \quad (69)$$

where  $q_1$  is the amount of heat taken in by the engine at the temperature  $T_1$ . Since (art. 15)  $w = q_1 - q_2$ , we find from the first and last members of equation 68 that  $q_1 \frac{T_2}{T_1}$  represents the total amount of heat  $q_2$  given out

by the engine at the temperature  $T_2$  during the complete cycle—that is, the unavailable energy or the quantity of heat not convertible into work. Only if  $T_2$ , the temperature of the sink, could be reduced to  $0^\circ A$  would  $q_2$  be zero and the total amount of heat  $q_1$  given to the engine be all converted into work  $w$ . In that event the efficiency of the engine would be unity, or, in the usual notation, 100 per cent.

From equation 69 we concluded that the maximum efficiency  $e_f$  obtainable from any engine is entirely determined by the temperatures  $T_1$  and  $T_2$  between which it works. As  $T_2$  approaches  $0^\circ A$ , the efficiency of the Carnot engine approaches 100 per cent. Since  $T_2$  can never be reduced to  $0^\circ A$ , the efficiency of the most efficient heat engine is always less than 100 per cent.

### 19. Entropy

*Definition of Entropy.*—Because of the frequent occurrence of the ratio of the amount of heat  $\Delta q$  taken in by a system, to the temperature  $T$  at which it is taken in, Clausius introduced the name entropy,  $\Delta s$ . This, as mentioned earlier, is defined by

$$\Delta s = \frac{\Delta q}{T} \quad \left. \right\} (70)$$

or

$$s_B - s_A = \int_A^B \frac{dq}{T}$$

where the small letters  $s$  and  $q$  refer respectively to the entropy and heat per gram of the substance and  $A$  and  $B$  are the initial and final states. By convention  $dq$  is positive (+) when heat flows into the substance and negative (-) when heat flows out of the substance and into the surroundings.

*The Total Change in Entropy of a System or Working Substance in Passing Through a Reversible Cycle.*—The system includes the engine or working substance together with its surroundings, the source and the sink. Let the working substance—water vapor, for example—pass through the re-

versible cycle represented by the closed figure 8. Divide the complete cycle into a number of small Carnot cycles bounded by adiabatics and isothermals as indicated. Thus we are replacing the single engine, working along the curve  $ACBDA$ , by a number of small reversible engines, each working on one of the cycles into which the area has been divided. It is clear from the figure that the greater the number of Carnot cycles into which the large cycle is divided, the more nearly is the effect of the sum of all the small Carnot cycles equivalent to the effect of the large

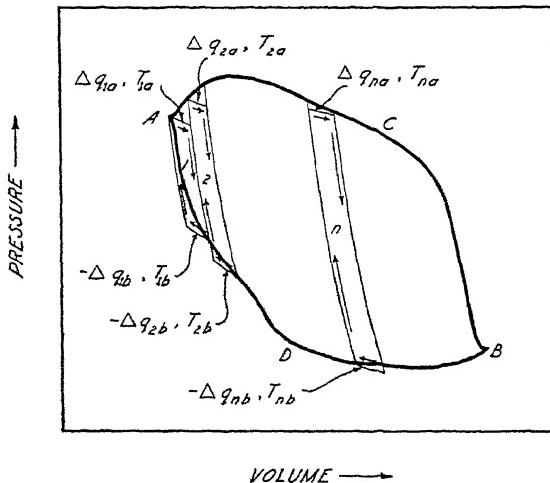


Fig. 8.—A generalized reversible cycle divided into little Carnot cycles.

single one. The sum of all the quantities of heat,  $\Delta q_a$ ,  $\Delta q_{2a}$ ,  $\Delta q_{3a}$ , . . .  $\Delta q_{na}$ , . . . taken in by all the small separate reversible engines from the source (that is, from the surroundings) at the different temperatures,  $T_a$ ,  $T_{2a}$ ,  $T_{3a}$ , . . .  $T_{na}$ , . . . respectively, equals the total amount of heat taken in from the source by the large single engine. The sum of all the quantities of heat,  $-\Delta q_b$ ,  $-\Delta q_{2b}$ ,  $-\Delta q_{3b}$ , . . .  $-\Delta q_{nb}$ , . . . given out to the sink (that is, to the surroundings) by the small separate reversible engines at the temperatures  $T_b$ ,  $T_{2b}$ ,  $T_{3b}$ , . . .  $T_{nb}$ , . . . respectively, equals the total amount of heat given out by the large single engine. Thus in the limit when the number of small cycles is extremely great, the system of small engines is thermodynamically equivalent to the single large one. The signs of the quantities  $\Delta q_a$  and  $\Delta q_b$  are defined in accordance with the conventions mentioned in connection with equation 70.

Consider the small single  $n$ th cycle. We have, according to equation 67,

$$\frac{\Delta q_n}{T_n} - \frac{\Delta q_n}{T_{2n}} = 0. \quad (71)$$

To find the total change in entropy  $\Delta s$  in going around the complete cycle  $ACBDA$ , we must sum up all the small changes in entropy produced by all the small cycles. According to equation 71, the change in entropy in each small completed cycle is zero. We have, accordingly, for the following summation,

$$\Delta s = \left( \frac{\Delta q_a}{T_a} - \frac{\Delta q_b}{T_b} \right) + \left( \frac{\Delta q_{2a}}{T_{2a}} - \frac{\Delta q_{2b}}{T_{2b}} \right) + \dots + \left( \frac{\Delta q_{na}}{T_{na}} - \frac{\Delta q_{nb}}{T_{nb}} \right) + \dots = 0. \quad (72)$$

Hence we conclude that *the total change of entropy of a system or working substance in any reversible cycle, no matter what the path, is zero.* Equation 72 is equivalent in the limit to

$$\Delta s = \int^{(ACBDA)} \frac{dq}{T} = 0. \quad (73)$$

*The Change in Entropy  $\Delta s$  of a Working Substance in Going Reversibly from a State A to a State B.*—Consider the change in entropy in going around the complete cycle  $ACBDA$ , figure 8. This may be split up into two parts—one in going along  $ACB$ , the other along  $BDA$ . According to equation 73, we have then, for the total change,

$$\Delta s_{(ACB)} + \Delta s_{(BDA)} = 0$$

or

$$\Delta s_{(ACB)} = -\Delta s_{(BDA)}.$$

Since the sequence of the letters in the subscripts indicates the direction of the path followed and since when we change our path to the opposite direction we merely change the sign of the entropy change,  $\Delta s$ , without changing its magnitude, we therefore have

$$\Delta s_{(ACB)} = \Delta s_{(ADB)}. \quad (74)$$

Since  $ACB$  and  $ADB$  are any arbitrary paths, equation 74 says that no matter what path we take in going from the state  $A$  of the working substance to the state  $B$ , the change in entropy  $s$  is the same as long as the change is carried out reversibly. *The change in entropy  $\Delta s$  in any reversible process depends, therefore, only on the coordinates of the initial and final states, A and B.* This is unlike such quantities as the work  $w$  and the heat  $q$ , which depend wholly on the manner of going from  $A$  to  $B$ . The fact that the change in entropy  $\Delta s$  of a substance, in going from a state  $A$  to a state  $B$ , is independent of the manner in which the change is carried out, is what makes entropy so important in thermodynamics.

*The Total Change in Entropy of a System or Working Substance in Passing through an Irreversible Cycle.*—In all the previous considerations, we

in calculating the change in entropy in going from the state *A* to the state *B* when the transformation is reversible. If, for example, water vapor confined at a fixed pressure is allowed to escape into a vessel at a lower pressure, the vapor undergoes an increase of entropy even though no heat passes into or out of the system. To calculate the change in entropy of a natural process by equation 70 in going from *A* to *B* in such a case, we replace the irreversible transformation by a reversible one, connecting the same two states *A* and *B*. The change of entropy can then immediately be calculated by means of equation 70 as will be illustrated below. As previously shown, it is immaterial what reversible path we take between *A* and *B* in calculating the change of entropy  $\Delta s$ . All paths will give the same value for  $\Delta s$  (eq. 74).

✓ *Change in Entropy When Heat Flows Spontaneously from a Hot to a Cold Body.*—Consider two bodies in contact, one at a temperature  $T_1$ , the other at  $T_2$ . Both bodies are insulated so that there is no heat interchange with the surroundings. Assume that a quantity of heat  $dq$  flows by conduction from the body at the higher temperature  $T_1$  to the other at  $T_2$ . The decrease in entropy of the hotter body is

$$ds_1 = -\frac{dq}{T_1},$$

and the increase in entropy of the colder body is

$$ds_2 = \frac{dq}{T_2}.$$

The total change of entropy of the system as a whole is

$$ds = ds_1 + ds_2 = -\frac{dq}{T_1} + \frac{dq}{T_2} = dq \frac{(T_1 - T_2)}{T_1 T_2} > 0 \quad (78)$$

since  $T_1 > T_2$ . Thus the total change in entropy  $ds$  of the whole system is positive whenever an amount of heat  $dq$  flows spontaneously from one point to another.

Generalizing, therefore, in any irreversible process (that includes all natural processes) the entropy always increases. It will always tend toward a maximum. When this maximum is reached, the available energy will become zero, and all parts of the system will acquire a uniform temperature. The Second Law of thermodynamics, re-expressed in terms of entropy, states that in all natural processes the total entropy of a completely isolated system will increase. That is, a system is subject to spontaneous changes if any process can occur in which  $ds > 0$ . When the state of equilibrium has been reached by the system,  $ds = 0$  for any conceiv-

able infinitesimal change that the system might undergo. Never in nature will entropy tend to decrease spontaneously. If it could, heat would tend to flow from a colder to a hotter body, and this would be in violation of the Second Law of thermodynamics. According to this law, as will be recalled from article 14, no self-acting device unaided by any external agency can transfer heat from a body of lower temperature to one of higher temperature.

Comparing the First and Second laws of thermodynamics, we may say that entropy stands in the same relation to the Second Law as energy stands to the First. Entropy and its characteristics, which embody the Second Law, predict in what direction the process or reaction will be carried out. On the other hand, the First Law, that of the conservation of energy, predicts the quantitative relation between the various kinds of energy involved in case the reaction is carried out.

*Dependence of the Entropy of an Ideal Gas on the Temperature T, Volume v, and Pressure p.*—The change in entropy is calculated according to the fundamental equation 70:

$$\Delta s = s_B - s_A = \int_A^B \frac{dq}{T}. \quad (79)$$

Since the change in entropy is a function entirely of the limits A and B and since only two of the variables  $T$ ,  $V$ , and  $p$  are needed to define the state of an ideal gas (art. 1 and 2),  $dq$  then can always be expressed in terms of any two of the variables. Since the integrand of equation 79 contains  $T$ , let us express  $dq$  first, for example, in terms of  $T$  and  $v$ . From equation 49:

$$dq = de + pdv,$$

where we use  $p$  since it refers to pressure in a gas. From equation 51,  $de = c_v dT$ ; and from the ideal-gas law (eq. 367),  $p = \frac{RT}{v}$ . Therefore

$$dq = c_v dT + RT \frac{dv}{v}.$$

Equation 79 therefore becomes:

$$\begin{aligned} s_B - s_A &= c_v \int_A^B \frac{dT}{T} + R \int_A^B \frac{dv}{v} \\ &= c_v \ln \frac{T_B}{T_A} + R \ln \frac{v_B}{v_A}. \end{aligned} \quad (80)$$

This gives the change of the entropy of an ideal gas in terms of the corresponding changes of temperature  $T$  and volume  $v$ . Eliminating  $v$  by means of the ideal gas equation,  $pv = RT$ , and eliminating  $R$  in equation

80 by equation 370,  $c_p - c_v = R$ , we can express the change in entropy in terms of corresponding changes of pressure  $p$  and temperature  $T$  (after again substituting  $R$  from equation 370), as follows:

$$s_B - s_A = c_p \ln \frac{T_B}{T_A} - R \ln \frac{p_B}{p_A}. \quad (81)$$

Similarly, equation 80, using the same two expressions, may be transformed into

$$s_B - s_A = c_v \ln \frac{p_B}{p_A} + c_p \ln \frac{v_B}{v_A}, \quad (82)$$

giving the change in entropy in taking a gas from a pressure  $p_A$  and volume  $v_A$  to another pressure  $p_B$  and volume  $v_B$ .

*Dependence of Entropy  $s$  of Any Substance on the Temperature  $T$  While the Pressure  $P$  Remains Constant.*—Recalling the analytic definition of entropy, equation 70, we have

$$s_B - s_A = \Delta s = \int_{T_A}^{T_B} \frac{dq}{T}. \quad (83)$$

The heat  $dq$  is here in too general a form. Let us secure a form more suitable to heat transformations carried out at constant pressure and involving the temperature  $T$ . From the First Law of thermodynamics, we have (eq. 49)

$$dq = de + dw = de + Pdv.$$

Since we are here postulating that  $P$  is constant, we may write

$$\begin{aligned} dq &= de + d(Pv) \\ &= d(e + Pv). \end{aligned}$$

The heat content  $h$  was defined by  $(e + Pv)$  (eq. 54). At constant pressure, therefore,

$$dq = dh = c_p dT$$

because  $dh = c_p dT$  (eq. 56). Equation 83 therefore becomes

$$s_B - s_A = \int_{T_A}^{T_B} \frac{c_p dT}{T} = \int_{T_A}^{T_B} \frac{dh}{T} \quad (84)$$

or

$$s_B = s_A + \int_{T_A}^{T_B} \frac{c_p dT}{T}. \quad (85)$$

Let us consider equation 85 when  $T_A$  is  $0^\circ\text{A}$ . We shall assume then that the entropy  $s_A$  will equal zero. This assumption, which forms the basis of

the Third Law of thermodynamics, will be discussed in article 20. Equation 85 then becomes

$$s_B = \int_0^{T_B} \frac{c_p dT}{T}. \quad (86)$$

Equation 86 gives the absolute value of the entropy per gram of a substance. To evaluate this,  $c_p$  must in general be known as a function of  $T$ . At the higher temperatures,  $c_p$  may be considered as nearly constant. This is by no means true in the neighborhood of  $0^\circ A$ , where the specific heat  $c_p$  approaches zero. The variation of the specific heat  $c_p$  at constant pressure with temperature  $T$ , particularly in the vicinity of  $0^\circ A$ , will be considered in article 20.

*Change of Entropy during an Isothermal Process.*—We shall use equation 84 for calculating the change in entropy  $\Delta s$  when ice is melted reversibly and isothermally at  $273^\circ A$ . In connection with an italicized statement earlier in this article, it will be recalled that to calculate the change in entropy of a substance in going from one state,  $A$ , to another,  $B$ , one must choose a reversible path between the two states and then carry out the integration of

$$s_B - s_A = \int_A^B \frac{dh}{T}. \quad (87)$$

At the melting point of ice, for example, the two phases, ice and water, are in equilibrium, and the process of fusion is therefore reversible: if the external temperature is raised by an infinitesimal amount, the solid will melt; and if it is lowered by an infinitesimal amount, the liquid will freeze. In other words, there is always a state of balance between the two opposing tendencies when the melting is carried out isothermally and reversibly at  $273^\circ A$ .

Since the process is isothermal, we have

$$s_B - s_A = \frac{1}{T} \int_A^B dh \quad (88)$$

where  $s_B$  denotes the entropy per gram of water and  $s_A$  the entropy per gram of ice. Here, obviously, the integral  $\int_A^B dh$  is simply the heat of fusion of ice. It might also be regarded as the heat of reaction. Since the heat  $dh$  required to melt 1 gram of ice at  $273^\circ A$  is 79.6 calories per gram,  $\int_A^B dh = 79.6$  calories per gram. Consequently,

$$\Delta s = \frac{79.6}{273} = 0.29 \text{ calories per gram per degree absolute.} \quad (89)$$

Thus at  $273^{\circ}$  A the entropy of a gram of water is 0.29 calories per degree greater than that of a gram of ice.

In the same manner, we may calculate the change in the entropy of a gram of water upon being vaporized. We must always remember that in calculating changes of entropy, the path of integration chosen for equation 87 must be reversible whether the process is isothermal or not.

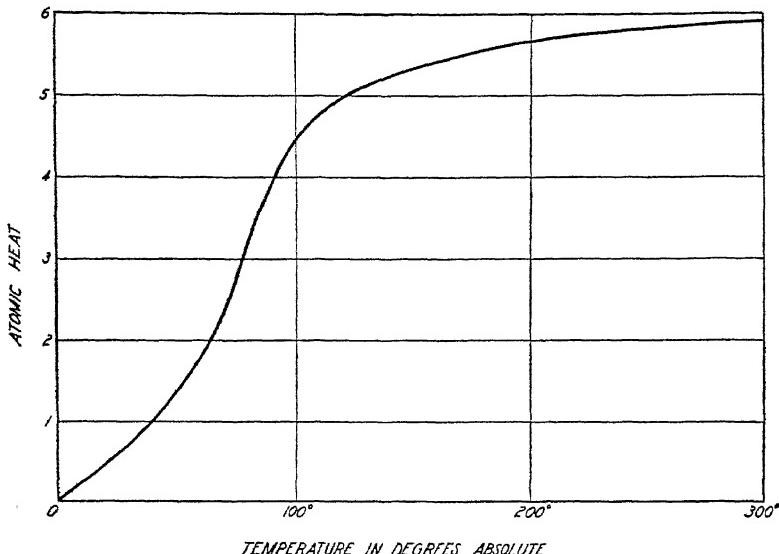


Fig. 9.—Typical way in which the atomic heat depends on temperature.

#### 20. Specific Heat of Solids at Low Temperatures and the Third Law of Thermodynamics

Most of the chemical elements, particularly those of high atomic weight, show approximately the same value for the product of specific heat and atomic weight at ordinary temperatures. This product, usually called the atomic heat, was first shown experimentally by Dulong and Petit to be about 6.2 calories per gram atom. The value 6.2 was readily accounted for under the classical theory of thermodynamics and the kinetic theory of matter.

In 1911, however, Nernst's critical examination of the specific heat of many different substances at constant pressure over a wide range of temperatures showed that this rule held true only in special instances. At ordinary temperatures the atomic heat was constant—approximately 6 calories per gram atom. At very low temperatures, however, it was found to be very small and to approach zero at  $0^{\circ}$  A. A typical case is shown in figure 9. In 1912, Debye presented a theory of the variation of atomic

heat with change of temperature that gave curves coinciding very closely with those observed experimentally by Nernst. Debye's theory is based upon the quantum theory.

Figure 10 for water is a particular case of figure 9, taken from data in the International Critical Tables. According to figure 10, the specific heat

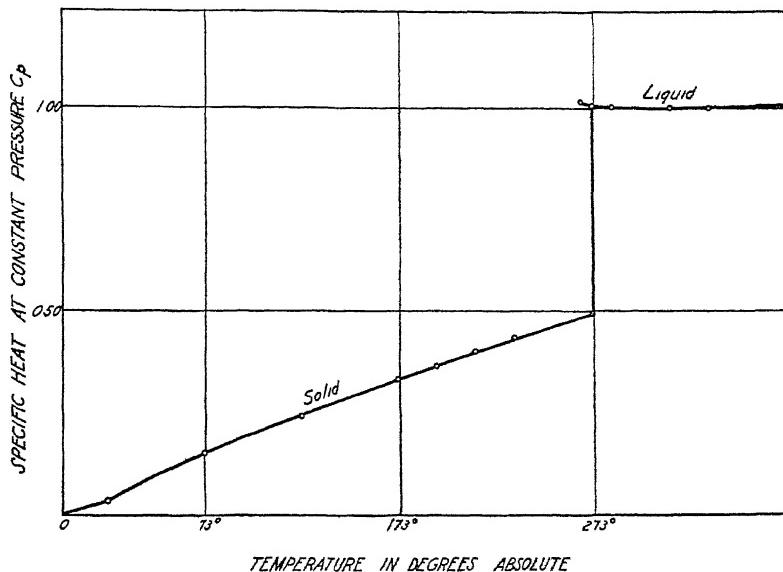


Fig. 10.—The dependence of specific heat of water at constant pressure, on temperature. Extension of the curve to the left represents supercooling.

of ice at constant pressure is zero at  $0^\circ$  A but gradually increases, until at  $273^\circ$  it is approximately 0.5 calorie per gram. Upon melting, the specific heat of the water suddenly jumps to approximately 1.0 calorie per gram.

A knowledge of the variation of the specific heat at constant pressure  $c_p$  is extremely important in computing the total value of such thermodynamic functions as entropy  $s$ , equation 90; total heat content  $h$ , equation 91; and the free energy  $f$ , equation 416. The total entropy  $s$  of a body, in general, is defined by

$$s = \int_0^T \frac{c_p dT}{T} + K$$

where  $K$  is an arbitrary additive constant, independent of the pressure, state of aggregation, and special chemical modification of the substance. This statement with respect to  $K$  has been amply verified by Nernst (1906) and by others.

The additive constant  $K$  can be arbitrarily taken as zero at  $0^\circ$  A. Such a selection makes the entropy  $s$  zero at absolute zero since, as was previously pointed out, the specific heat  $c_p$  becomes zero at  $0^\circ$ . This leads to the following expression for the value of the absolute specific entropy of a substance such as water:

$$s = \int_0^T \frac{c_p dT}{T}. \quad (90)$$

Equation 90 is merely the analytic expression and a special case of Nernst's general heat theorem, which serves to define the absolute value of the entropy. This theorem was stated by Planck as follows: "As the temperature diminishes indefinitely, the entropy of a chemical homogeneous body of finite density approaches indefinitely near to a definite value, which is independent of the pressure, the state of aggregation, and of the special modification." When we set the arbitrary constant  $K$  equal to zero (eq. 90), the theorem defining the absolute value of the entropy becomes, according to Planck: "As the temperature diminishes indefinitely, the entropy of a chemical homogeneous body of finite density approaches indefinitely near to the value zero." This basic theorem is often called the Third Law of thermodynamics. This means that at  $0^\circ$  A, we shall always assume the entropy of a substance to be zero.

Knowing the specific heat  $c_p$  at constant pressure as a function of the temperature, we can calculate the heat content  $h$  of a substance at any temperature  $T$ . The heat content has previously been defined according to equation 56, which becomes

$$h = \int_0^T c_p dT + h_0$$

where  $h_0$  is the heat content at  $0^\circ$  A. Now if  $h_0$  is arbitrarily put equal to zero at  $0^\circ$ , we have

$$h = \int_0^T c_p dT. \quad (91)$$

This arbitrarily makes the heat content  $h$  equal to zero at  $0^\circ$ .

## PROPERTIES OF FREE ENERGY USEFUL IN A THERMO-DYNAMIC STUDY OF SOIL MOISTURE

### 21. Characteristics of Free Energy ✓

*Use of Free Energy in Describing Natural Processes.*—As has been shown (art. 19), any natural process is characterized by an increase in the sum of the entropies  $ds$  of all parts of the system involved in the process. Also, if there is any possible change in the system for which  $ds > 0$ , the system is subject to spontaneous changes and cannot remain in equilibrium. If, furthermore, the system is in a state of equilibrium, its total change of entropy  $ds$  for all conceivable infinitesimal changes that the system might be made to undergo is zero—that is,  $ds = 0$ .

These facts are somewhat analogous to the conditions for spontaneous change and for equilibrium in the studies of mechanics, electricity, magnetism, and some aspects of the hydrodynamics of soil moisture. These studies make use of a quantity called "potential" that corresponds to entropy in the field of thermodynamics. A system is said to be subject to a spontaneous change if, in any conceivable infinitesimal change that it might be allowed to undergo, its total potential energy  $\psi$  will decrease—that is,  $\Delta\psi < 0$ . During a spontaneous change, as will be noticed, the entropy  $s$  of a system always increases, whereas the potential energy  $\psi$  of the system always decreases; that is,  $\Delta s > 0$  and  $\Delta\psi < 0$  describe the same conditions. If a system is in equilibrium, the change of the potential energy of the system  $\Delta\psi$  for all conceivable infinitesimal changes that the system might undergo is zero; both  $\Delta s = 0$  and  $\Delta\psi = 0$  describe the conditions for equilibrium.

The term "entropy" was invented to describe and deal with energy changes associated primarily with the transformations of heat into other forms of energy in the field of thermodynamics. "Potential," on the other hand, was invented to deal with changes of mechanical energy and of work in the fields of mechanics, electricity, and magnetism. The two terms and sets of criteria for equilibria arose originally somewhat independently of each other to deal with their respective types of energy changes as found in nature.

\*In studies on soil moisture and plant relations, the criteria set up by entropy alone, for energy changes and for equilibria, are far too general for most purposes, whereas those set up by potential are sometimes too limited and restricted. Potential, for example, takes no explicit account of the effect of temperature on the total energy change of a system. Fortunately, another function, called "free energy"  $f$  was invented many years ago in the field of thermodynamics. This function combines all the criteria and characteristics of both potential and entropy that are most

useful in the study of the thermodynamics of soil moisture and its use by plants. For example, it permits one to take account, explicitly, of the effect of temperature on the energy changes of a soil-moisture system, which may include several phases in equilibrium with each other. It is less general than entropy, which makes it more convenient and practical than entropy in the study of some actual problems. As will be shown below, the free energy  $f$  is defined in terms of entropy.

*Thermodynamic Properties of Free Energy.*—Absolute free energy  $f$  is defined by the two equations

$$f = e + Pv - Ts = h - Ts. \quad (92)$$

These are equivalent because  $h = e + Pv$  (eq. 54). Here  $e$  represents the internal energy,  $v$  the specific volume,  $h$  the heat content, and  $s$  the entropy, of the substance under consideration.

The student might reasonably ask why such functions as heat content  $h$  and absolute free energy  $f$  are defined in such an apparently arbitrary manner with seemingly so little preliminary justification. Such functions, however, are usually arrived at during a mathematical analysis of a particular problem. Sometimes, in such analyses, a certain combination of mathematical terms describing physical quantities appears frequently in the equations, and the investigator may for convenience give it a particular name. The justification for introducing such quantities can become evident only as the student grows sufficiently familiar with their characteristics to appreciate their convenience and power in the analyses of problems. The genesis of such a function might be illustrated by the introduction of the term  $h$  for the combination  $(e + Pv)$  in the expression of the specific heat at constant pressure  $c_p$ , discussed in connection with equation 53.

Now the total work  $dw$  performed by a system may, in general, be separated into two parts: the work of expansion  $Pdv$  against a pressure  $P$ , and any other mechanical work  $dw_m$ , including electrical work, that the system might perform. In general, therefore, the total work  $dw$  may be represented by

$$dw = Pdv + dw_m. \quad (93)$$

Differentiating the first of equations 92, we have

$$df = de + Pv - Tds - sdT. \quad (94)$$

According to the First Law of thermodynamics (eq. 47), we have

$$de = dq - dw. \quad (95)$$

Now, in any reversible process, since  $ds = \frac{dq}{T}$  (eq. 70), we have  $dq = Tds$ , which, in combination with equation 93, makes equation 95 become

$$de = Tds - Pdv - dw_m. \quad (96)$$

Substituting 96 into 94, we have

$$df = -sdT + vdP - dw_m. \quad (97)$$

For isothermal changes,  $dT = 0$ , and equation 97 becomes

$$df = vdP - dw_m. \quad (98)$$

If the pressure  $P$  is constant during the change, then

$$df = -dw_m$$

or

$$-df = dw_m. \quad (99)$$

According to equation 99, if a reversible change is taking place in a system at a constant temperature and pressure, the work  $dw_m$  done by the system, excluding the work of expansion against the constant pressure  $P$ , equals the decrease of the free energy ( $-df$ ) of the system during the change. Thus a finite decrease in the free energy  $-df$  is a measure of the maximum work  $\Delta w_m$  (including both electrical and mechanical work but excluding any mechanical work of expansion against a constant pressure  $P$ ) that can be performed by the system, at constant temperature and pressure, on its surroundings.

Let us now consider finite isothermal changes in a system from a state  $A$  to a state  $B$ . Since  $dT = 0$ , we therefore have, from equation 98,

$$\Delta f = \int_A^B df = f_B - f_A = \int_A^B vdP - \int_A^B dw_m. \quad (100)$$

If the pressure remains constant throughout the isothermal change of state, then  $dP = 0$ , and equation 100 becomes

$$\Delta f = f_B - f_A = - \int_A^B dw_m = -\Delta w_m. \quad (101)$$

According to equation 101, in finite isothermal, isobaric changes of state of a system from  $A$  to  $B$ , the increase in the free energy  $\Delta f$  of the system equals the work  $\left( - \int_A^B dw_m \right)$  that must be performed on the system in carrying it from state  $A$  to state  $B$ . As already pointed out, this integral does not include work of expansion against a pressure  $P$ , as is seen from equation 93.

Equation 101 may also be interpreted as follows: if we let  $A$  represent the datum (see art. 40), the free energy  $\Delta f$  of a system in the state  $B$  with respect to the datum  $A$  is equal to the work that must be done on the system at constant temperature and pressure to bring it from the datum  $A$  to the state  $B$ . Another way of interpreting equation 101 is: the decrease in the free energy  $-\Delta f$  of the system in going from state  $A$  to state  $B$  equals the total work done isobarically and isothermally by the system on the surroundings, excluding any work of expansion against a constant pressure  $P$ .

If, on the other hand, no work is performed during the isothermal change, but there is a change in the pressure  $P$  (that is, when  $\int_A^B dw_m = 0$ ), then equation 100 becomes

$$\Delta f = f_B - f_A = \int_A^B vdP. \quad (102)$$

Thus the mere increase of the hydrostatic pressure  $P$  on the system will increase its free energy.

If a reversible process occurs at constant temperature and pressure, with no work done except an expansion against a constant pressure  $P$ , equation 102 becomes

$$\Delta f = f_B - f_A = 0. \quad (103)$$

Equation 103, as will be shown later, describes the conditions at equilibrium or where two or more phases remain in equilibrium. If, for example, water and vapor are in equilibrium at 100° C and if heat is added to the water so as to vaporize 1 gram of water at 100° C and at 1 atmosphere, then equation 103 says that the absolute free energy  $f_B$  in the vapor state equals that in the liquid state  $f_A$ . This follows because the temperature and pressure remain unchanged and because no work is done during the change except the expansion against the constant pressure  $P$  of the atmosphere.

Knowing the absolute value of the entropy  $s$  as defined by equation 90 and knowing the heat content  $h$  as defined by equations 57 and 91, we can express the absolute free energy  $f$ , previously defined by

$$f = h - Ts, \quad (104)$$

in another useful form. From equations 90 and 57, equation 104 becomes

$$f = \int_0^T c_p dT - T \int_0^T \frac{c_p dT}{T}. \quad (105)$$

Hence if  $c_p$  is known as a function of temperature, all three of the thermodynamic functions  $s$ ,  $h$ , and  $f$  may be computed as indicated above.

At this point, the reader should clearly distinguish between the meanings of the absolute free energy  $f$  and what we shall simply call "free energy,"  $\Delta f$ . The letter  $f$  defined by equations 92 denotes the absolute free energy (that is, the free energy of a substance when  $0^\circ A$  is used as the reference point), whereas we shall represent by  $\Delta f$  the difference in free energy between the substance in any particular state and the chosen reference point, both being usually at the same temperature. For simplicity we shall speak of  $\Delta f$  as the free energy of the substance. We shall always understand it to represent the difference between the absolute free energy  $f$  of the substance in the standard state and in the state in question.

*Relation between Changes in Free Energy and Work Performed in Reversible and Irreversible Processes.*—In all reversible processes (eq. 99), the maximum amount of work  $dw_m$  obtainable from a system equals the decrease in its free energy. That is,

$$-\Delta f = \Delta w_m. \quad (106)$$

In practice, however, all processes are irreversible to some extent; otherwise they would have to occur so slowly as never to be completed. If an isothermal process is to occur with a finite velocity, the process will be irreversible, and some of the mechanical work will be lost in the form of heat, so that we always find

$$-\Delta f > \Delta w_m'. \quad (107)$$

In other words, the mechanical work  $\Delta w_m'$  performed in a natural process or transformation is less than the decrease in free energy occurring in the process. The difference ( $\Delta w_m - \Delta w_m'$ ) represents a loss in mechanical energy. It generally becomes heat energy at a temperature too low to be available for work in the system under consideration.

A simple example in mechanics might clarify the preceding ideas. The relations given above may be illustrated by figure 11. By analogy, since temperature is here not involved, we shall take the level  $A$  where  $h = 0$  as representing our absolute zero of free energy  $f$ . Here  $h$  has of course not the same meaning as it has been given previously. Our system is here composed of the weight  $M_1$ , which by analogy we shall regard as the working substance, and the weight  $M_2$ , which we shall regard as the surroundings, both weights being hung from the frictionless pully  $P$  by a weightless rope. As  $M_1$  moves downward, work  $dw_m$  is done on the surroundings  $M_2$ . All changes in the system will be carried out at constant temperature and pressure. Reference to the discussion following equation 101 shows that the absolute free energy  $f$ , in ergs, of the working

substance  $M_1$  at  $B$  with respect to the point  $A$  is given by the potential energy (in the c.g.s. system)

$$f = h M_1 g \text{ ergs.} \quad (108)$$

While  $M_1$  travels downward, work  $\Delta w_m$  is performed on the surroundings  $M_2$ ; numerically this is equal to

$$\Delta w_m = h M_2 g \text{ ergs.} \quad (109)$$

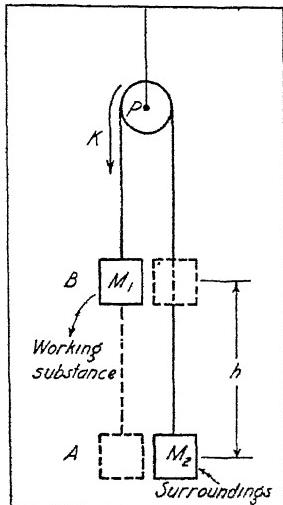


Fig. 11.—Mechanical model for illustrating the meaning of the term "free energy."

Since  $M_1 > M_2$ ,

$$h M_1 g > h M_2 g;$$

and therefore (eq. 110, 111) we have

$$-\Delta f > \Delta w_m',$$

which corresponds to inequality 107 for an irreversible process. The greater  $M_1$  is with respect to  $M_2$  (that is, the more irreversible the process), the greater the above inequality.

The question now is, when  $M_1$  moves downward, what happens to the free energy that is lost and not stored in the surroundings as available energy? It is mainly dissipated as heat when  $M_1$  strikes the bottom at  $B$ , since the directed kinetic energy of the downward motion of  $M_1$  is converted into random heat movements of the individual molecules. In

We shall first consider an irreversible change represented by inequality 107 above. In order that  $M_1$  may move downward with finite velocity, the weight  $M_1$  must be greater than  $M_2$  in order that there may be a net driving force  $K$ . The greater the disparity between  $M_1$  and  $M_2$ , the greater the force  $K$ , the greater the velocity of movement, and consequently (as we shall show) the greater the irreversibility of the process.

When  $M_1$  moves from  $B$  to  $A$ , the decrease in free energy of the working substance is (eq. 108)

$$-\Delta f = h M_1 g \text{ ergs.} \quad (110)$$

The work done on the surroundings, consisting here of the weight  $M_2$ , is

$$\Delta w_m' = h M_2 g \text{ ergs.} \quad (111)$$

addition, when  $M_1$  strikes the bottom at  $B$ , some of the lost energy may go into energy of deformation of the bodies as well as into sound.

Let us now consider the case when the working substance  $M_1$  moves down reversibly. Only in the limit when  $M_1 = M_2$ , and therefore when  $M_1$  moves downward with infinite slowness will the decrease in the free energy  $-\Delta f$  of the working substance  $M_1$  equal the work  $\Delta w_m$  performed by the system on  $M_2$ , for, under these conditions, the net driving force  $K$  tending to move  $M_1$  downward must be an infinitesimal, in order to develop only an infinitesimal amount of kinetic energy in  $M_1$ . The decrease in the free energy of the working substance from equation 108 is

$$-\Delta f = h M_1 g \text{ ergs}; \quad (112)$$

and the work performed reversibly on the surroundings (eq. 109) is

$$\Delta w_m = h M_2 g \text{ ergs}. \quad (113)$$

Since  $M_1 = M_2$ , we have in the limit, from equations 112 and 113, for the reversible process, which must be carried out infinitely slowly,

$$-\Delta f = \Delta w_m,$$

corresponding to equation 106 of a reversible process.

The foregoing examples demonstrate that any natural spontaneous process must be to some extent irreversible. This follows because the forces of the system cannot all be completely balanced at all times. If they were, in order to satisfy the condition of reversibility, the process would go on with such infinite slowness that it would never be completed in a finite time. To carry out the process within a finite time, there must be an inequality in magnitude of opposing forces; in other words, there must be a resultant driving force  $K$  of the process. The greater  $K$  is, the greater the irreversibility. In all such cases, as is shown by the illustration above, the decrease of the free energy  $-\Delta f$  is greater than the useful work accomplished  $\Delta w_m'$ . That is,

$$-\Delta f > \Delta w_m'.$$

We have considered above the change in the free energy  $-\Delta f$  of the system when there has been interchange of useful work  $\Delta w_m'$  with the surroundings. We shall now consider a case where  $\Delta w_m' = 0$ —that is, where no work is done on the surroundings during the process, and the energy is instead dissipated into unavailable forms such as heat at too low a temperature to be available. In this case we have from inequality 107

$$-\Delta f = -(f_2 - f_1) > 0.$$

Assume a closed system in which spontaneous changes are taking place, where there is no interchange of work, and where, accordingly,  $\Delta w_m' = 0$ . This might correspond to a spontaneous change in a system such as one composed of a moist and a dry soil placed in contact. Suppose, for convenience, we have enough wet and dry soil so that the total weight of moisture in both is 1 gram. Moisture will spontaneously go from the moist to the dry soil, and the process will be irreversible. Here  $f_1$  represents the average absolute free energy of the moisture in the entire system initially, and  $f_2$  the average absolute free energy in the entire system after the spontaneous change has taken place. Since  $\Delta w_m' = 0$ , inequality 107 shows that

$$-\Delta f = -(f_2 - f_1) > 0 \quad (114)$$

or

$$\Delta f = (f_2 - f_1) < 0.$$

That is,

$$f_2 < f_1. \quad (115)$$

As moisture continues spontaneously to flow from the moist to the dry soil, the initial average absolute free energy  $f_1$  of the entire system decreases to the final value  $f_2$ .

We may thus conclude that when any spontaneous change occurs at constant temperature and external pressure, the absolute free energy of the system will invariably decrease; that is, the free-energy change  $\Delta f$  is always negative. Or, stated algebraically, we have for all spontaneous changes

$$\Delta f < 0. \quad (116)$$

Never in any spontaneous change will the free energy increase.

*Condition of Equilibrium.*—For an isothermal reversible process occurring at constant pressure, it was shown that  $-\Delta f = \Delta w_m$ . If we are dealing with an isolated system that can perform no net work on the surroundings except an expansion against constant pressure  $P$ , we must set  $\Delta w_m = 0$ ; that is,  $\Delta f = 0$ .

Now, at equilibrium, all possible infinitesimal displacements of the system are also reversible—that is, all forces are completely balanced except for infinitesimal differences. The work done,  $\Delta w_m$ , in any possible infinitesimal displacement of the system, when at equilibrium, must accordingly equal zero, for there is no resultant force in any direction at equilibrium and hence  $\Delta f = 0$ . Therefore, since for any process occurring at constant temperature and pressure at equilibrium we have  $\Delta f = 0$ , the state of equilibrium may be defined by

$$\Delta f = 0. \quad (117)$$

*Comparison of Free Energy with Potential.*—The discussion above brings out another similarity of free energy to the potential energy as used in such fields as mechanics, electricity, magnetism, and soil moisture. The following tabulated comparisons between potential and free energy will illustrate some of their points of similarity. Earlier in this article we considered some of the differences between them that make free energy superior for present purposes. Other comparisons will be made later.

	Free energy $f$	Potential $\Phi$
Condition for equilibrium	For any infinitesimal change of system, $\Delta f = 0$	For any infinitesimal change of system, $\Delta\Phi = 0$
Necessary condition for spontaneous change	$\Delta f < 0$	$\Delta\Phi < 0$
Usual conditions of system for spontaneous change	Constant temperature and pressure	Constant temperature and pressure
Typical spontaneous changes	<p>Soil moisture moves spontaneously from wet soils, where <math>f</math> is high, to drier soils, where <math>f</math> is lower</p> <p>.....</p> <p>.....</p>	<p>Soil moisture moves spontaneously from wet soils, where <math>\Phi</math> is high, to dry soils, where <math>\Phi</math> is lower</p> <p>.....</p> <p>Electricity moves spontaneously from points where <math>\Phi</math> is high to points of lower <math>\Phi</math></p> <p>.....</p> <p>Masses under influence of gravitational field move downward from points of high <math>\Phi</math> to points of lower <math>\Phi</math></p>

*Specific Free Energy of Several Phases of the Same Substance in Equilibrium with Each Other.*—Often we shall be concerned with several phases of a substance in equilibrium with each other, such as ice and water. In order to deal with the energy changes involved, let us give the absolute free energy term  $f$  additional meaning. In the past, the amount of mass to which the term  $f$  referred was not always specifically stated. It sometimes denoted the absolute free energy of the entire system, which in our present case would be composed of the total amount of the ice and water present. This definition of  $f$  is too general; it does not permit us to deal with the separate phases that compose the entire system or with their interrelations. For this reason we shall redefine  $f$  to mean the absolute specific free energy per unit mass of the substance in a single phase. We shall speak of this as absolute specific free energy, or as absolute free

energy of the substance in that phase. Changes in the free energy of our system will now consist of changes in absolute free energy of the unit mass within the same phase or of changes in absolute free energy of the unit mass in going from one phase to another. As was shown earlier, if two phases are in equilibrium with each other, any infinitesimal change in the variables of state of the system (for example  $T$  and  $p$ ) will not change its total absolute free energy. Also, when a gram of ice melts by the addition of heat or a gram of water freezes by the removal of heat, no change in the total free energy of the system occurs so long as both the temperature and the pressure remain constant.

The change in the absolute free energy of the system when 1 gram of ice melts under equilibrium conditions of temperature and pressure is given (eq. 117) by

$$\Delta f = 0. \checkmark$$

Here  $\Delta f$  represents the change in free energy of 1 gram of the substance when it changes state. That is,  $\Delta f = 0$  simply states the fact that the free energy of the substance is the same in the two phases. As long as the two phases are present together, equilibrium will be maintained. For finite changes of the free energy of the system at equilibrium, we therefore have

$$\Delta f = (f_2 - f_1) = 0.$$

That is, if  $f_1$  is the absolute specific free energy of the substance (ice) in the initial phase and if  $f_2$  is the absolute specific free energy of the substance (water) in the final phase, we have

$$f_1 = f_2. \quad (118)$$

Thus, if two phases coexist at equilibrium, their absolute specific free energies are the same.

It will now be interesting to inquire how the absolute specific free energies  $f_1$  and  $f_2$  will be altered by changing the temperature of the system from the equilibrium temperature considered above, at which both phases are in equilibrium with each other, to some other temperature. Throughout the following considerations, we shall assume the pressure to remain constant. If the temperature of the two phases should be raised, the change of ice to water is of course spontaneous. That is (inequality 107), since  $\Delta w_m' = 0$ , we have

$$\Delta f = (f_2 - f_1) < 0$$

as the free-energy change of the reaction where  $f_1$  is the absolute specific free energy of the initial state (ice) and  $f_2$  is the absolute specific free energy of the final state (water), or

$$f_2 < f_1. \quad (119)$$

Thus, above 0° C the absolute free energy of the ice is greater than the absolute free energy of water. If one phase (ice) having the absolute free energy  $f_1$  changes spontaneously to another (water) having the absolute free energy  $f_2$ , the absolute free energy of the former must be the greater. This statement agrees with the generalization that the free energy decreases in all spontaneous changes.

If, on the other hand, the temperature should be lowered below 0° C, water will of course pass into ice spontaneously. If we now consider liquid water ( $f_2$ ) as the initial state and ice ( $f_1$ ) as the final state, we have (inequality 107 again)

$$\Delta f = (f_1 - f_2) < 0,$$

from which we can derive the relation for the free-energy change  $\Delta f$  for the imaginary reaction of ice melting into water below 0° C. It is clear, then, that

$$-\Delta f = (f_2 - f_1) > 0$$

or

$$f_2 > f_1. \quad (120)$$

Thus, below 0° C, the absolute free energy of water is greater than the absolute free energy of ice. If one phase (ice) having the absolute free energy  $f_1$  cannot change spontaneously to another (water) having the absolute free energy  $f_2$ , the absolute free energy of the former must be less. This agrees with the generalization that spontaneous changes never take place where the free energy of the system increases.

From the foregoing discussion, we may conclude that if several phases of the same substance are in equilibrium, the absolute specific free energies are the same in all phases of the system. More detailed and rigorous proof will be presented in article 22. If, however, the absolute free energy of any one phase should be greater than that of the others, then that phase will disappear into the others.

*Negative Character of the Free Energy of Unsaturated Soils.*—The discussion above shows clearly that the specific free energy of a system or substance decreases in any spontaneous change. Let us consider a body of free water in contact with an unsaturated soil. By common experience, water flows spontaneously from a body of free water (whose absolute specific free energy we shall call  $f_1$ ) into an unsaturated soil (whose absolute specific free energy we shall call  $f_2$ ). It is customary to use free, pure water under a pressure of 1 atmosphere (art. 62) as the zero point or datum for the free energy of soil moisture. Thus the free energy  $\Delta f$  of pure water under these conditions becomes zero. We have shown (inequality 107), in going from an initial state  $f_1$  to a final state  $f_2$ , that, for any spontaneous change in the case where  $\Delta w_m' = 0$ , it follows that

$$\Delta f = (f_2 - f_1) < 0. \quad (121)$$

Here  $\Delta f = f_2 - f_1$  represents the free energy of the unsaturated soil with respect to the reference point  $f_1$ . That is, the absolute free energy  $f_2$  of the unsaturated soil moisture is less than that of free, pure water. The inequality 121 states the general fact that the free energy  $\Delta f$  of soil moisture in all unsaturated soils is negative with respect to the commonly accepted datum, since  $\Delta f < 0$ .

Going a bit further, let us consider the relation between the magnitude and sign of the free energy  $\Delta f$  of a wet soil and those of a drier one. Since, as is commonly known, moisture will flow spontaneously from the wet to the dry soil and since we are here considering spontaneous changes, let us take the wetter soil as the initial state of the soil moisture having the absolute free energy  $f_1$  and the drier soil as the final state of the soil moisture having the absolute free energy  $f_2$ . For spontaneous changes (inequality 121), we have

$$f_2 < f_1. \quad (122)$$

Inequality 122 states the general fact that the absolute free energy  $f_2$  of the moisture in a comparatively dry soil is less than the absolute free energy  $f_1$  of that in a wet soil.

As was shown previously, the free energy  $\Delta f$  of the moisture of all unsaturated soils is negative. The free energy of the moisture is therefore always more negative in a drier soil than in a wetter soil. Only if the wet soil is saturated can its free energy, at the most, be zero.

## 22. The Equality between the Free Energies of Several Coexistent Phases

We have previously shown (eq. 118) somewhat indirectly, in discussing the various characteristics of free energy, that the free energies of two or more phases coexisting at equilibrium must be the same. We shall now show this, for the case where the temperature and pressure are equal in all phases, in a much more rigorous and direct manner.

All substances exist in different modifications between which transitions may occur. These modifications are often called the different phases of a substance, the most important examples being the different states of aggregation—for example, gaseous, liquid, and solid. In addition, we have the different allotropic modifications of a substance, which make up still other possible phases.

From article 4 we recall that if we have a function  $\phi$  of one or more variables and if we are at a maximum or minimum of the function  $\phi$ , then any slight change in any one or more of the variables will not change  $\phi$ . We shall represent slight variations in their magnitude by the symbol  $\delta$ . At a maximum or minimum of the function  $\phi$  we have

$$\delta\phi = 0$$

for any slight change of the variables. Conversely,  $\delta\phi = 0$  serves to determine the values of the variables for which  $\phi$  has a maximum or minimum. For example, taking the simplest case where  $\phi$  is a function of but one variable,  $x$ , we find that at any maximum or minimum of  $\phi$  the first derivative of  $\phi$  is zero. Any infinitesimal variation  $\delta x$  in the neighborhood of either  $C$  or  $A$  (fig. 3), the maximum and minimum of  $\phi$ , is seen to produce no variation  $\delta\phi$  in the function  $\phi$ ; that is,  $\delta\phi = 0$  for infinitesimal variations of  $\delta x$ . If, however, we focus our attention on any other point  $B$  of the curve, we note that slight variations  $\delta x$  do produce appreciable variations  $\delta\phi$  of the function  $\phi$ .

We will also utilize the following mathematical fact: If  $\phi$  is a function of one or more variables and if we wish it to remain constant for all possible variations of the independent variables, then

$$\delta\phi = 0$$

for all infinitesimal changes of the variables upon which  $\phi$  depends. The changes in the variables must therefore so adjust themselves that  $\delta\phi = 0$ . If, for example,  $\phi = xy$ , and  $\phi$  is to remain constant during changes of  $x$  and  $y$ , then  $\delta\phi = 0 = x\delta y + y\delta x$ , which serves to define the relation that must exist between changes of  $x$  and  $y$ .

We shall now prove that when two or more phases are in thermodynamic equilibrium with each other, and their temperatures and external pressures are equal, then their free energies must all be the same. To prove this we have merely to assume the First and Second laws of thermodynamics as well as the conservation of matter. It was shown for a specific case (connected with eq. 78) that *when a system has attained equilibrium, the total entropy S of the system has attained a maximum for the given values of the total mass, energy, and volume of the system.* This is a general characteristic of entropy at equilibrium. Our problem is thus to find the conditions which make  $S$  a maximum subject to the conditions that the total mass  $M$ , the total internal energy  $E$ , and the volume  $V$  remain constant. Hence one condition for the coexistence of several phases of a system in thermodynamic equilibrium is that

$$\delta S = 0. \quad (123)$$

That is, any slight displacement or change of the system composed of the several phases in equilibrium with each other does not alter the total entropy of the system. Certain almost self-evident subordinate conditions follow, furthermore, according to the previous paragraph. First,

$$\delta V = 0, \quad (124)$$

which states that the total volume of the system remains constant. Then, too,

$$\delta V = 0, \quad (125)$$

which states that the total internal energy of the system remains constant. Also,

$$\delta E = 0, \quad (126)$$

which states that the total mass  $M$  of the system remains constant—none is created or added and none is destroyed or taken away. That is, with a given mass, energy, and volume of the system,  $\delta S = 0$  at equilibrium.

Let us now consider the simple example of a system composed of only two coexisting phases. Let  $s$ ,  $v$ , and  $e$  represent the entropy, volume, and internal energy of the substance per unit mass—that is, the specific values. Let  $m$  represent the mass of the two phases, and let  $X$  be a fraction such that  $mX$  represents the mass of one of the phases. Then  $m(1 - X)$  will represent the mass of the other phase. In what follows we shall assume for simplicity that  $m$  is unity; that is, we are dealing with only 1 gram of the substance. The quantities associated with one of the phases will be distinguished by a prime; those with the other by a double prime. The specific entropy of the system then becomes

$$s = Xs' + (1 - X)s'', \quad (127)$$

and the specific volume

$$v = Xv' + (1 - X)v'', \quad (128)$$

and the specific internal energy

$$e = Xe' + (1 - X)e'', \quad (129)$$

and the specific mass of the system  $m$ , which we shall set equal to unity

$$m = Xm + (1 - X)m. \quad (130)$$

Because of equation 123, 127 becomes

$$\delta s = 0 = X\delta s' + (1 - X)\delta s'' + (s' - s'')\delta X. \quad (131)$$

Similarly, we have

$$\delta v = 0 = X\delta v' + (1 - X)\delta v'' + (v' - v'')\delta X \quad (132)$$

and

$$\delta e = 0 = X\delta e' + (1 - X)\delta e'' + (e' - e'')\delta X \quad (133)$$

and

$$\delta m = 0 = m\delta X - m\delta X. \quad (134)$$

On the other hand, in accordance with the Second Law of thermodynamics stated by equations 49 and 70, we have

$$\delta s' = \frac{\delta q'}{T'} = \frac{\delta e' + P' \delta v'}{T'} \quad (135)$$

and

$$\delta s'' = \frac{\delta q''}{T''} = \frac{\delta e'' + P'' \delta v''}{T''}. \quad (136)$$

We want to express  $\delta e''$  and  $\delta v''$  in terms of  $\delta e'$  and  $\delta v'$ . To do this, solve equations 132 and 133 for  $(1 - X)\delta v''$  and  $(1 - X)\delta e''$  respectively, and substitute these values in equation 136. We then have

$$(1 - X)\delta s'' = -\frac{X\delta e'}{T''} - \frac{XP''\delta v'}{T''} - \left[ \frac{e' - e''}{T''} + \frac{P''(v' - v'')}{T''} \right] \delta X.$$

Substituting this as well as equation 135 into equation 131, we have

$$0 = X\delta e' \left[ \frac{1}{T'} - \frac{1}{T''} \right] + X\delta v' \left[ \frac{P'}{T'} - \frac{P''}{T''} \right] \\ + \delta X \left[ s' - s'' - \frac{e' - e''}{T''} - \frac{P''(v' - v'')}{T''} \right]. \quad (137)$$

As may be seen from equations 131, 132, and 133, the variations  $\delta e'$ ,  $\delta v'$ , and  $\delta X$  (the quantities associated with but one of the phases) can be carried out quite arbitrarily and independently of each other and still satisfy the three equations that define the states of equilibrium between the two phases. The reason is that no matter what values are given to  $\delta e'$ ,  $\delta v'$ , and  $\delta X$ , the other variations in these equations can be given the proper values to still satisfy the three equations defining the state of equilibrium. Since the variations  $\delta e'$ ,  $\delta v'$ , and  $\delta X$  of equation 137 are therefore quite independent of each other and can assume any arbitrary value, equation 137 can be satisfied at all times only when each of the three expressions in square brackets vanishes separately. This will be the case for the first two brackets when

$$T' = T'' \quad \text{and} \quad P' = P''. \quad (138)$$

For simplicity, let  $T$  and  $P$  denote the equal temperatures and pressures respectively of equation 138. The third bracket then becomes

$$s' - s'' - \frac{e' - e''}{T} - \frac{P(v' - v'')}{T} = 0$$

or

$$-s' + \frac{e'}{T} + \frac{Pv'}{T} = -s'' + \frac{e''}{T} + \frac{Pv''}{T}$$

or

$$-s'T + e' + Pv' = -s''T + e'' + Pv''. \quad (139)$$

Now it will be recalled (eq. 92) that we defined the absolute specific free energy  $f$  of a substance by

$$f = e - sT + Pv.$$

We see, therefore, that equation 139 above actually states that

$$f' = f''. \quad (140)$$

We thus conclude from the foregoing that if two phases are in equilibrium with each other and are at the same temperature and under the same pressure, then, as an inevitable consequence, both phases must possess the same absolute specific free energy. What was shown to hold for the free energies of two phases in equilibrium at the same temperature and pressure is readily seen to hold for any number of phases of a substance in equilibrium with each other.

This fact makes the quantity called "free energy" tremendously important when we are dealing with systems consisting of several phases in equilibrium with each other. Soil moisture, for example, may exist in the vapor, liquid, and solid states. If we know the free energy of the vapor in equilibrium with both the liquid and frozen soil moisture, we also know the free energy of the liquid soil moisture, as well as that of the solid soil moisture.

In the above proof, the pressure was made the same on the different phases at equilibrium to demonstrate the equality of free energy in the phases. This is not generally necessary. Cases when the pressures are not the same on the different phases at equilibrium will be discussed in articles 26, 30, and 41.

### 23. Effect of Temperature on the Free Energy

We wish to find how the free energy changes as the temperature is changed. Suppose we consider, for example, 1 gram of water at a given temperature and pressure, possessing a given amount of free energy. From equation 97 we have

$$df = -sdT + vdP - dw_m. \quad (141)$$

If the pressure remains constant and if no work is done on the surroundings, equation 141 becomes

$$df = -sdT \quad (142).$$

or

$$\left(\frac{\partial f}{\partial T}\right)_P = -s. \quad (143)$$

Thus the rate of change of the absolute free energy with respect to change of temperature equals the negative of the specific entropy. Applied to soil moisture, this means that the rate of change of the absolute free energy of soil moisture with temperature equals the negative of its specific entropy.

Suppose we go further and, instead of considering the change in the absolute free energy of water in going from one temperature to another, discuss the following case. At constant temperature  $T$  and pressure  $P$ , let a process (fig. 12) occur such that the absolute free energy in the initial

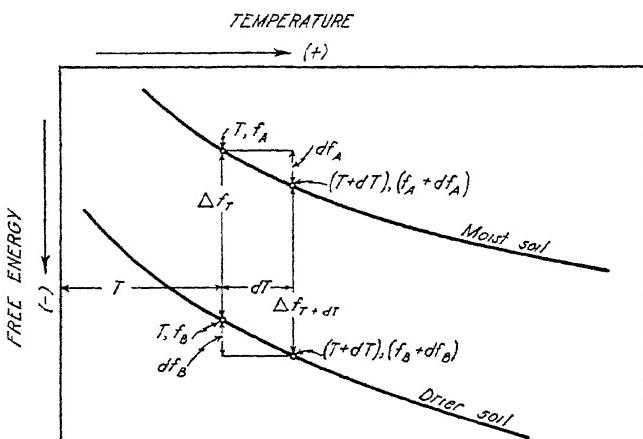


Fig. 12.—Dependence of specific free energy on temperature.

state is  $f_A$ , in the final state  $f_B$ , so that the change in the absolute free energy during the process is  $\Delta f_T = f_B - f_A$ . If the same process is carried out in exactly the same manner and at the same pressure, but at a different temperature  $T + dT$ , the absolute free energy in the initial and final states will be  $f_A + df_A$  and  $f_B + df_B$  respectively, giving a different value  $\Delta f_{T+dT}$  for the change in free energy at the temperature  $T + dT$ . We wish to find how the change in free energy  $\Delta f_T$  of the process depends on temperature. Suppose, for example, we have determined the change in free energy  $\Delta f_T$  of a gram of water in being carried from a drier soil to a wetter soil at the temperature  $T$ . We shall now wish to determine how this change of the free energy  $\Delta f_T$  involved in the transformation, change, or process is affected if the process is carried out at a different temperature  $T + dT$ . In the following discussion all changes of the process at the same temperature are denoted by  $\Delta$ , whereas changes in the process in going from one temperature to another are denoted by  $d$ .

Since the process is carried out at constant pressure without the per-

formance of work, we have (eq. 142) the change  $df_A$  of the absolute free energy of the initial state *A* for a change  $dT$  of the temperature

$$df_A = -s_A dT \quad (144)$$

and for the change  $df_B$  of the absolute free energy of the final state *B* because of a change of temperature  $dT$ ,

$$df_B = -s_B dT. \quad (145)$$

The pressure in state *A* is to remain constant with all variations of temperature; so, likewise, is the pressure in state *B*. On the other hand, the pressure in state *A* will not in general be the same as in state *B*. The subscript *P* in equation 146 below denotes these facts.

From equations 144 and 145, we have

$$d(f_B - f_A) = d(\Delta f) = -(s_B - s_A)dT$$

or

$$\left( \frac{d(\Delta f)}{dT} \right)_P = -(s_B - s_A) = -\Delta s_P. \quad (146)$$

Thus, for example, the rate of change of the free energy  $\Delta f$  of soil moisture with respect to changes of temperature  $T$ , with the restrictions placed on the pressure as given above, equals the negative of the specific entropy,  $\Delta s_P$ , of the soil moisture, both  $\Delta f$  and  $\Delta s_P$  being measured with respect to free water in this example.

#### 24. The Effect of Osmotic Pressure on the Free Energy of a Liquid

Suppose we have a pure solvent in contact with a solution through a semipermeable membrane as in figure 13. If the pressures on *A* and *B* are the same, the system will not be in equilibrium. Solvent will then flow from *C* into *D*. Also the vapor pressure  $p$  over *A* will be less than  $p_0$  over *B*, which would cause a resultant movement of solvent from *B* to *A* through the vapor phase if the pistons were not present. Only when we increase the pressure on the solution by a definite amount  $\Delta P$ —by means of a piston, for example—will the resultant flow of solvent through the semipermeable membrane from *C* to *D* be stopped and the vapor pressure  $p$  of the solvent over *A* become equal to  $p_0$  over *B*. The pressure  $\Delta P_0$  on the solution, which will just stop the movement of solvent from *B* to *A* in the vapor phase as well as from *C* to *D* in the liquid phase, is known as the “osmotic pressure” of the solution. It will be zero if no solute is present, and will increase as the amount of dissolved material increases.

From a kinetic viewpoint the situation may be described as follows, when we are not dealing with concentrated solutions. The presence of dissolved materials lowers the escaping tendency of the solvent molecules,

and thus holds back a definite fraction of those that would normally escape. On this basis, for example, if one fifth of the molecules of the solution were solute molecules, both the vapor pressure and escaping tendency of the solvent would be reduced to four fifths of their values for the pure solvent. Thus more of the solvent will move from *B* to *A* as well as from *C* to *D* than in the opposite direction, and there will consequently be a net flow of solvent into the solution. The escaping tendency of the solvent on the right side is the same throughout all parts of the solution. It is also the same throughout the pure solvent on the left side, but it has a higher value there than on the right. A quantitative measure of the

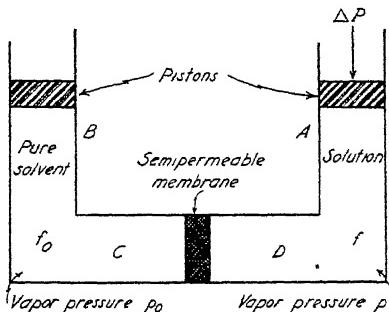


Fig. 13.—Equilibrium between a solution and the pure solvent through a semipermeable membrane.

escaping tendency of the solvent is its vapor pressure. Under the conditions postulated in the figure, the vapor pressure over *A* is less than that over *B*; that is,  $p$  is less than  $p_0$ . Likewise the escaping tendency of the solvent on the right side is less than that on the left. Now, to establish equilibrium between the two sides, the vapor pressure or escaping tendency of the solvent on the right side must be increased. This may be accomplished by placing the solution under a hydrostatic pressure  $\Delta P_o$ , now called the osmotic pressure, such that the vapor pressure originally having the value  $p$  is raised to  $p_0$ . The vapor pressure on the right, a measure of the escaping tendency of the solvent, is then equal to that on the left, and equilibrium is established. Incidentally the hydrostatic pressure  $\Delta P_o$  (that is, the osmotic pressure) required to raise the vapor pressure from  $p$  to  $p_0$  can be immediately calculated according to equation 239.

The osmotic pressure  $\Delta P_o$ , which equals the hydrostatic pressure  $\Delta P$  that must be applied to the solution to establish equilibrium, is by van't Hoff's law (eq. 226) given to a first approximation by

$$(\Delta P_o)v = x_2RT, \quad (147)$$

which is nothing more than the familiar ideal-gas equation. According to this equation, the dissolved material in a relatively dilute solution may be considered as behaving exactly like an ideal gas at the same temperature  $T$  and volume  $v$  as it occupies in the solution. The resultant solute pressure  $\Delta P$  on the semipermeable membrane is found experimentally, for dilute solutions for which semipermeable membranes have been produced, to be approximately the same as the gas pressure or osmotic pressure  $\Delta P_o$  given by equation 147.

Having considered above quantitatively some of the characteristics of osmotic pressure, let us now show that the free energy of the solvent of a solution (with respect to the pure solvent) is given by

$$\Delta f = -v\Delta P_o \quad (148)$$

where  $v$  is the specific volume of the solvent and  $\Delta P_o$  is the osmotic pressure of the solution. For example, if the solvent is water, the free energy  $\Delta f$  of the solvent is numerically equal but opposite in sign to the osmotic pressure  $\Delta P_o$ , since the specific volume of water is unity in the c.g.s. system. Here, as will be recalled, we always take the zero point of free energy as that of free, pure water.

In proving equation 148, let us assume, as before, that we have a solution in contact with the pure solvent through a semipermeable membrane (fig. 13). The absolute specific free energy and the vapor pressure of the pure solvent are  $f_0$  and  $p_0$ , respectively; those of the solvent of the solution,  $f$  and  $p$ , respectively. As before, let  $\Delta P_o$  denote the osmotic pressure—that is, the hydrostatic pressure that must be placed upon the solution in order to raise the escaping tendency, vapor pressure, and absolute free energy of the solvent of the solution to that of the pure solvent in the side  $B$ . We shall determine the specific free energy  $\Delta f$  of the solution with respect to the pure solvent by calculating the amount of free energy required to raise the absolute free energy  $f$  of the solution to that of the pure solvent  $f_0$ . That is, we shall calculate the change in the free energy of the solution caused by applying a pressure  $\Delta P_o$  to the solution.

By equation 102 we can calculate the change in the absolute free energy produced by an increase of the hydrostatic pressure on the solution:

$$\Delta f = f_B - f_A = \int_{P_A}^{P_B} v dP. \quad (149)$$

In our present case the initial absolute free energy and hydrostatic pressure on the solution are  $f$  and zero, respectively. Thus, using our present notation in the equation above,  $f_A = f$ , and  $P_A = 0$ . In the final state the absolute free energy of the solvent and the pressure on the solution are  $f_0$  and  $\Delta P_o$ , respectively. Thus in the final state,  $f_B = f_0$  and  $P_B = \Delta P_o$ .

Since the specific volume  $v$  of a liquid is practically independent of pressure, equation 149 then becomes

$$f_0 - f = \int_0^{\Delta P_o} v dP = v \Delta P_o. \quad (150)$$

The quantity  $(f_0 - f)$  actually gives the free energy of the pure solvent with respect to the solution. We want, instead, the free energy  $\Delta f$  of the solution with respect to the pure solvent, which is the negative of  $(f_0 - f)$ . This is

$$f - f_0 = \Delta f = -v \Delta P_o \quad (151)$$

or, in differential form,

$$\left( \frac{\partial f}{\partial P_o} \right)_T = -v. \quad (152)$$

When equation 151, giving the dependence of the free energy on osmotic pressure, is compared with equation 156, giving the dependence of the free energy on hydrostatic pressure, the two are seen to have the same form except for the difference in sign.

### 25. The Effect of Pressure on the Free Energy of Liquids and Gases

Let us assume that we have 1 gram of a fluid contained in a volume  $v$ . We wish to determine the dependency of its free energy on the pressure applied to it. We shall assume that all changes are isothermal and that the only mechanical energy changes involved are those due to the expansion and contraction against the external pressure. These considerations will answer, for example, the question as to how the free energy of water due to hydrostatic pressure increases with depth in a reservoir; or how the free energy of soil moisture, due to hydrostatic pressure resulting from the adsorptive force field surrounding the soil particle, increases as the surface of the soil particle is approached.

For isothermal changes without the performance of work except for an expansion against the pressure  $P$ , we found (eq. 102)

$$\Delta f = f_B - f_A = \int_A^B v dP. \quad (153)$$

If, therefore, we are dealing with almost incompressible liquids for which the specific volume  $v$  is practically unaffected by changes of pressure, we have for the free-energy change  $\Delta f$  due to a change in hydrostatic pressure,

$$\Delta f = f_B - f_A = v \int_{P_A}^{P_B} dP \quad (154)$$

or

$$f_B = f_A + v \int_{P_A}^{P_B} dP. \quad (155)$$

That is, if water has a free energy  $f_A$  initially and the pressure is increased from  $P_A$  to  $P_B$ , the free energy becomes  $f_B$  (eq. 155). For finite changes, equation 154 also becomes

$$\Delta f = f_B - f_A = v \Delta P. \quad (156)$$

Digressing momentarily, we will note that equation 153 may be placed in the very useful form

$$\left( \frac{\partial f}{\partial P} \right)_T = v \quad (157)$$

where the subscript  $T$  indicates that the temperature is kept constant during the variation of pressure  $P$ . According to equation 157, the rate of change of the specific free energy of a liquid with respect to changes of pressure equals the specific volume of the liquid.

Returning again to equation 156, let us apply it to liquid water whose specific volume  $v$  in the c.g.s. system is equal to unity. We then have

$$\Delta f = \Delta P. \quad (158)$$

That is, for water the free-energy change  $\Delta f$  due to the change in hydrostatic pressure is numerically equal to the change in hydrostatic pressure  $\Delta P$ . On the other hand, as will be shown later or can be seen from equation 151, the free energy of water due to the presence of dissolved material is numerically equal to the negative of the osmotic pressure. The two expressions, therefore, have the same form except for a minus sign.

We have just shown the dependence of the free energy on pressure for incompressible fluids—that is, liquids. Let us now consider the same dependence for gases, which are compressible. In the present case, the specific volume  $v$  is no longer constant but varies with the pressure. Let us here assume that we are dealing with gases which follow the ideal gas law so that  $pV = RT$ , according to equation 367. We then have (eq. 153)

$$\Delta f = f_B - f_A = \int_{p_A}^{p_B} v dp = RT \int_{p_A}^{p_B} \frac{dp}{p} = RT \ln \frac{p_B}{p_A}. \quad (159)$$

Equation 159 indicates that the free energy  $\Delta f$  of the gas increases as its pressure increases isothermally. If  $p_B$  is less than  $p_A$ , the logarithm is negative, which indicates that the free energy of the gas in the state  $B$  at the pressure  $p_B$  is less than in the state  $A$  at the pressure  $p_A$ .

Let us apply equation 159 in the evaluation of the free energy of soil moisture to illustrate its meaning and usefulness. By convention we have considered that our datum or zero point of reference for the free energy of soil moisture is that of free, pure water. As has previously been shown (art. 22), free energy always has the same value in all phases which are in

equilibrium with each other; that is, the free energy of the water vapor above free water must also equal that of free water itself. Thus if we wish to determine the free energy of soil moisture—often a very difficult thing to do directly—we have merely to deal with the vapor in equilibrium with it. The free energy of the soil moisture whose vapor pressure is  $p_B$  is then given by equation 159, where  $p_A$  is the vapor pressure of the datum—that is, of free, pure water at the same temperature.

At this point we shall digress for a moment and observe a relation existing between the work done during the isothermal expansion of an ideal gas and the change in its free energy. The most general change of the free energy  $\Delta f$  was given by equation 97, which may in this case (since there is here no distinction between  $p$  and  $P$ ) be written

$$\Delta f = -s\Delta T + v\Delta p - \Delta w_m$$

where  $\Delta w_m$  included all the work performed by the system except that of expanding against an external pressure  $p$ . For an ideal gas we will show that the term  $v\Delta p$  equals the work of expansion against the external pressure  $p$ . At present we are dealing merely with isothermal changes in volume of a gas under a variable external pressure  $p$ , so that both  $\Delta T = 0$  and  $\Delta w_m = 0$ . We therefore have

$$\Delta f = v\Delta p. \quad (160)$$

We wish to show that the decrease in the free energy of the ideal gas upon expansion equals the work done by it during isothermal expansion against the variable pressure  $p$ . That is, the term  $v\Delta p$  in equation 97 takes care of the work  $p\Delta v$  of isothermal expansion of a gas. In other words,

$$-\Delta f = -v\Delta p = p\Delta v. \quad (161)$$

Differentiating the ideal gas equation for isothermal changes of volume and pressure, we have

$$\Delta(pv) = p\Delta v + v\Delta p = \Delta(RT) = 0,$$

or

$$v\Delta p = -p\Delta v. \quad (162)$$

Combining this with equation 160, we finally obtain 161, showing that either the term  $-v\Delta p$  or  $p\Delta v$  represents the work done by the ideal gas during isothermal changes of volume under the variable external pressure. In other words, equation 97 when applied to an ideal gas is equivalent to

$$\Delta f = -s\Delta T - p\Delta v - \Delta w_m.$$

## 26. Effect of a Force Field on the Free Energy of Water

For the change in free energy  $\Delta f$  during any transformation, equation 97 gives

$$\Delta f = -s\Delta T + v\Delta P - \Delta w_m. \quad (163)$$

At present we want to derive an expression for the change in free energy  $\Delta f$  per unit mass experienced by the water particle  $P$  in moving it from  $B$  to  $A$  (fig. 14), for example, where these points are located in a force field.

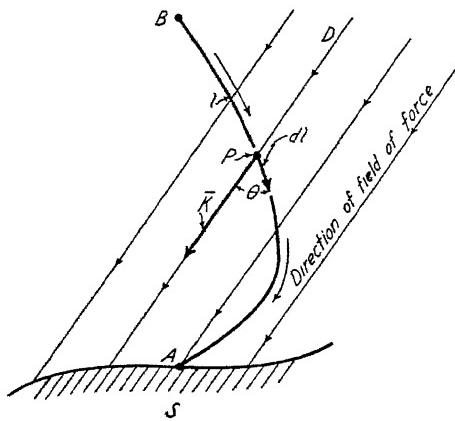


Fig. 14.—Relation between the direction of the force field acting on a body and its path of motion.

During this change neither the temperature nor the external pressure comes into consideration, since we shall regard both these as constant; and therefore both  $\Delta T$  and  $\Delta P$  are zero. Equation 163 then becomes

$$-\Delta f = \Delta w_m \quad (164)$$

which says that the work  $\Delta w_m$  per unit mass done by the particle of water on the surroundings in moving from  $B$  to  $A$  equals the decrease in its specific free energy ( $-\Delta f$ ). According to our convention, a positive  $\Delta w_m$  indicates work done by the water particle (that is, the working substance) and a minus  $\Delta w_m$  indicates work done on the water particle by the surroundings. Of course, if the water moves in the opposite direction (that is, from  $A$  to  $B$ ), work  $-\Delta w_m$  will be done by the particle on the surroundings; and the increase in specific free energy of the particle is  $\Delta f$ . These changes are, of course, carried out reversibly, so that the work done by the particle is always equal to that done on the surroundings.

Obviously, this form of free energy is identical with the term "potential" as used throughout the domain of mechanics, electricity, and magnetism; potential is merely a special kind of the numerous forms of free

energy. The great generality and superiority, for some purposes, of the function called "free energy" thus become evident.

The work done per unit mass by a particle on the surroundings in going from a point  $B$  to a point  $A$  is defined according to mechanics by

$$\Delta w_m = \int_B^A \bar{K} \cdot d\bar{l} \quad (165)$$

where the vector  $\bar{K}$  represents both the magnitude and direction of the field of force at the element of the path  $d\bar{l}$ . The vector  $d\bar{l}$  represents the element of the path both in direction and magnitude, and the dot between the two vectors indicates that the product of the magnitude of the two vectors must be multiplied by the cosine of the angle between the two vectors; that is,  $\bar{K} \cdot d\bar{l}$  is a scalar product. For those not acquainted with the vector notations,  $\Delta w_m$  may be expressed in a more common but often more cumbersome form:

$$\Delta w_m = \int_B^A K dl \cos \theta, \quad (166)$$

where  $K$  and  $dl$  are now scalar quantities.

The geometrical interpretation is clarified from a consideration of figure 14. As the particle of water  $P$  moves from a point  $B$  toward  $A$  along the path  $l$ , it does an amount of work  $\Delta w_m$  on the surroundings under the influence of the adsorptive force field of the soil particle  $S$ , for example. The direction of movement of the particle  $P$  makes an angle  $\theta$  with the assumed direction of the force field, and the total work  $\Delta w_m$  done by the water particle on the surroundings in moving from  $B$  to  $A$  is given by the integral in equation 166. Of course, if the particle moves in the opposite direction (that is, from  $A$  to  $B$ ) the work  $\Delta w_m$  changes its sign and becomes negative. We then have

$$\Delta w_m = \int_A^B K dl \cos \theta. \quad (167)$$

Although  $\Delta w_m$  appears positive according to equation 167 when the particle moves against the field of force, it is really not so, for the cosine of an obtuse angle is always negative. The disguised negative sign under the integral sign then makes  $\Delta w_m$  negative.

The expression for  $\Delta w_m$  takes on a particularly simple form if the line of action of the force is the same as that of the path of movement  $d\bar{l}$ . We have two cases. If the particle is moved in the direction of the force field (that is, from  $B$  to  $A$ ) then  $\cos \theta = 1$ , and

$$\Delta w_m = \int_B^A K dl.$$

The particle thus releases energy to the surroundings, since  $\Delta w_m$  is positive. If, on the other hand, the particle is moved in a direction opposite to the field (that is, from  $A$  to  $B$ ) the  $\cos \theta = -1$ , and we have

$$\Delta w_m = - \int_A^B K dl.$$

The water particle therefore gains energy from the surroundings, since  $\Delta w_m$  is negative; and work is done by the surroundings on the particle  $P$  to carry it from  $A$  to  $B$ .

Combining 164 with either 165 or 166, we have in vector notation

$$\Delta f = - \int_A^B \bar{K} \cdot \bar{dl}, \quad (168)$$

or in scalar notation

$$\Delta f = - \int_A^B K \cos \theta dl, \quad (169)$$

or in differential form

$$\frac{df}{dl} = - K \cos \theta.$$

As will be recalled from elementary physics, a scalar possesses only magnitude, whereas a vector possesses both magnitude and direction. Hence, as shown above, the rate of change of the free energy of the particle in any direction equals the negative of the component of the field in that direction.

In the special case where the path  $\bar{dl}$  coincides with the lines of force,  $\cos \theta = +1$ ; or, if we consider the projection  $K$  of the resultant force  $\bar{K}$  on the path of integration according to figure 14, equation 169 becomes

$$\Delta f = - \int_A^B K dl; \quad (170)$$

or, in differential form,

$$\frac{df}{dl} = - K \quad (171)$$

where  $K$  is a scalar rather than a vector. Thus, as mentioned earlier, after equation 117, this form of free energy is analogous to potential as used in mechanics, electricity, and magnetism. We conclude, then, that the change in the specific free energy  $\Delta f$  of the particle of water entailed by its being moved from a point  $A$  to a point  $B$  in a field of force is given by either of the line integrals in equations 168 and 169 or, in the special case where the direction of the path and field coincide, by equation 170.

To illustrate the meaning of these relations between free energy and

field of force, let us consider a vertical column of liquid water at equilibrium. We wish to study the dependence of the free energy of a water particle on its height  $\bar{y}$  above the lower surface  $S$  of the column (fig. 15). The distance  $\bar{y}$  will be measured from the bottom up, in which case  $\cos \theta$  is negative, since the positive direction of  $\bar{y}$  is opposite to the direction of the field. We suppose that the strength of the field is the same and equal to  $\bar{g}$  at all points above the water surface.

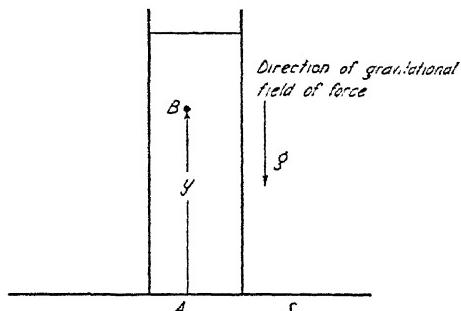


Fig. 15.—Column of water at equilibrium under a gravitational force field.

The total free energy  $\Delta f$  of the particle of water of unit mass at the point  $B$  is composed of two parts. One of these,  $\Delta f_P$ , is due to hydrostatic pressure; the other,  $\Delta f_F$ , is due to the position of the particle in the attractive force field. The first is given (eq. 153) by

$$\Delta f_P = \int_A^B v dP \quad (172)$$

and the second (eq. 169) by

$$\Delta f_F = \int_A^B g dy = g \int_A^B dy, \quad (173)$$

since the force  $K = g$  is independent of the value of  $y$  and  $\cos \theta = -1$ . The total free energy  $\Delta f$  of the particle of water at the point  $B$ , with respect to that at  $A$ , is then

$$\Delta f = \Delta f_P + \Delta f_F = \int_A^B v dP + \int_A^B g dy.$$

Since the column of water is in equilibrium, the total free energy of the water must be the same throughout all parts (eq. 117). That is,  $\Delta f = 0$ . Hence

$$v dP + g dy = 0,$$

or

$$\frac{dP}{dy} = -\frac{g}{v} = -g\rho \quad (174)$$

since  $v = \frac{1}{\rho}$  where  $\rho$  equals the density of the liquid. Equation 174 gives the well-known relation between the change of hydrostatic pressure and the change of height  $y$  in the column of water. It shows, in accordance with common experience, that as the height  $y$  increases, the hydrostatic pressure decreases.

### THERMODYNAMIC INTERRELATIONS AMONG THE PROPERTIES OF SOIL MOISTURE

#### 27. Relation between the Changes of Pressure $\Delta P$ and Temperature $\Delta T$ if Two Pure Phases Are to Remain in Equilibrium—Clausius-Clapeyron Equation

As will be recalled (art. 22), if two phases of a substance are in equilibrium with each other, their specific free energies must be the same. To fix our ideas, suppose the two phases are ice and water at 0° C and at 1 atmosphere. If now the pressure on the system is changed, the equilibrium is disturbed, and the free energies will no longer remain equal unless other changes are made in the system.

An increase of pressure, keeping the temperature unchanged, will cause the free energy of the ice to become greater than that of the water, because (eq. 157)

$$\left(\frac{\partial f}{\partial P}\right)_T = v. \quad (175)$$

Since for water, at 0° C,  $v = 1.000$  cc, the rate of increase of the free energy of water with respect to pressure is

$$\left(\frac{\partial f}{\partial P}\right)_T = 1.000. \quad (176)$$

And since for ice, at 0° C,  $v = 1.090$ , we have for ice

$$\left(\frac{\partial f}{\partial P}\right)_T = 1.090. \quad (177)$$

Evidently the free energy of the ice increases more than that of water for a given change of pressure. Thus the ice at 0° C will have a greater free energy at pressures higher than 1 atmosphere. As will be discussed later, the 1 atmosphere enters because of the peculiar definition of 0° C: 0° C is taken as the freezing point of water under a pressure of 1 atmosphere.

As will be recalled, free energy always decreases in a spontaneous change. Only when there is no possibility for the free energy to decrease will the system remain in equilibrium. From equations 176 and 177 we see that a given change in pressure causes a greater increase in the free energy of ice than it does in water. Consider ice and water at equilibrium under a given temperature and pressure. If now the pressure is raised, the free energy of the ice has a possibility of decreasing if it passes into the liquid state. All the ice accordingly melts. If, therefore, we have ice and water at equilibrium, an isothermal rise of pressure causes the ice to melt. By similar reasoning, since a given decrease in pressure causes a greater decrease of the free energy of ice than it does of water (eq. 176 and 177), it is clear that if ice and water are in equilibrium and the pressure is then decreased, all the water will pass into ice.

On the other hand, if we now keep the pressure constant and vary the temperature of the two phases originally in equilibrium, the specific free energies of the two phases will change differently according to equation 143, which is

$$\left(\frac{\partial f}{\partial T}\right)_P = -s. \quad (178)$$

According to equation 178, when the temperature is raised, the phase whose specific entropy  $s$  is the least will disappear completely, since its final free energy after the temperature change would be greatest. Likewise when the temperature is lowered, the phase whose specific entropy  $s$  is the greatest will disappear completely, since its final free energy after the temperature change would be greatest.

We have just considered how temperature and pressure affect the equilibrium of two phases originally in equilibrium with each other. One of the phases always disappears when either the temperature or pressure alone is changed from the equilibrium value. Let us now vary both temperature and pressure simultaneously in such a way that the amounts of the phases remain unchanged. We want to find the relation between the changes of the temperature  $\Delta T$  and pressure  $\Delta P$  that permit the phases to coexist. If  $f_1$ ,  $s_1$ , and  $v_1$  are the quantities associated with the first phase and if  $f_2$ ,  $s_2$ , and  $v_2$  are those of the second, and if the two phases are to be in equilibrium, we have (art. 22)

$$f_1 = f_2. \quad (179)$$

This means that when any change occurs in the system, the two free energies must change by an equal amount, namely,

$$df_1 = df_2. \quad (180)$$

Since only two variables such as  $P$  and  $T$  are required to fix the state of a substance, which we shall describe by the specific free energy  $f$ , and since the free energy is a perfect differential, we have (art. 2)

$$df_1 = \left( \frac{\partial f_1}{\partial P} \right)_T dP + \left( \frac{\partial f_1}{\partial T} \right)_P dT \quad (181)$$

and

$$df_2 = \left( \frac{\partial f_2}{\partial P} \right)_T dP + \left( \frac{\partial f_2}{\partial T} \right)_P dT. \quad (182)$$

Substituting 181 and 182 into 180 and recalling 143 and 157, we have

$$v_1 dP - s_1 dT = v_2 dP - s_2 dT. \quad (183)$$

This equation could, of course, have been obtained immediately from the generalized definition of the differential of the free energy given by equation 97, since no useful work  $dw_m$  is done. Rearranging 183 and collecting like terms, we have

$$\frac{dP}{dT} = \frac{s_2 - s_1}{v_2 - v_1}. \quad (184)$$

The quantity  $(s_2 - s_1)$  gives the change in specific entropy in going from phase 1 to phase 2 without change of temperature and pressure. For example, if we were transforming ice to water,  $(s_2 - s_1)$  would be the difference in entropy of the two phases. As before (eq. 84), we now also have

$$s_2 - s_1 = \frac{\Delta h}{T}$$

where  $\Delta h$  is the latent heat involved in changing a gram from the first phase to the second. If we are dealing with ice and water,  $\Delta h$  would be the well-known heat of fusion of ice  $l$ . The quantity  $(v_2 - v_1) = \Delta v$  represents the increase in volume per gram of the substance in going from the first to the second phase. Equation 184 then becomes the well-known Clausius-Clapeyron equation and is

$$\left. \begin{aligned} \frac{dP}{dT} &= \frac{\Delta h}{T \Delta v}, \\ dP &= \frac{\Delta h dT}{T \Delta v}, \end{aligned} \right\} (185)$$

or or for water

$$\frac{dP}{dT} = \frac{l}{T \Delta v}. \quad (186)$$

Although equation 186 was applied above to the equilibrium between the two phases liquid and solid, it applies equally well to the equilibrium between any two phases. For example, when water passes from liquid to vapor,  $\Delta h$  or  $l$  and  $\Delta v$  are both positive. Equation 186 therefore predicts that an increase of pressure  $dP$  causes an increase  $dT$  of the boiling point.

When water passes from ice to liquid,  $\Delta h$  or  $l$  is positive and  $\Delta v$  is negative, since ice contracts upon melting. Equation 186 predicts, therefore, that an increase of pressure  $dP$  causes a decrease  $dT$  of the melting point of water. This is borne out by the common phenomenon of regelation, a special case of which is the flowing of glaciers. The ice melts at those points where pressure is applied and refreezes elsewhere. In particular, equation 186 gives, for finite changes, the effect of hydrostatic pressure on the freezing-point depression  $\Delta T$  of a liquid as follows:

$$\Delta P = \frac{l\Delta T}{T\Delta v}. \quad (187)$$

If we are dealing with a solution, equation 187 applies quite independently of any dissolved material, the effect of which will be discussed in article 29.

The present article has taken up the treatment of the dependence of the freezing-point depression  $\Delta T$  on the hydrostatic pressure  $\Delta P$  when the latter has been kept the same on both phases. The treatment of the case where the pressure on one phase is different from that on the other is taken up in the more generalized treatment of article 30, and there is some plausible evidence that the freezing-point depression of relatively moist soils might fall under the latter case.

#### 28. Dependence of the Free Energy of a Liquid $\Delta f$ on the Hydrostatic Pressure $\Delta P$ as Measured by Its Freezing-Point Depression $\Delta T$

As will be recalled from equation 156, the free energy  $\Delta f$  of a liquid under a hydrostatic pressure  $\Delta P$  is given by

$$\Delta f = v\Delta P \quad (188)$$

where  $v$  denotes the specific volume of the liquid. Substituting equation 185 into 188, we have

$$\Delta f = \frac{v\Delta h}{T\Delta v} \Delta T \quad (189)$$

which expresses the free energy  $\Delta f$  of a liquid, due to hydrostatic pressure, in terms of its freezing-point depression  $\Delta T$ . For water,  $v = 1$  in the c.g.s. system, and  $\Delta h = l$ , so that

$$\Delta f = \frac{l\Delta T}{T\Delta v}. \quad (190)$$

**29. Relation between the Changes of Pressure  $\Delta P$  and Temperature  $\Delta T$  for a Solution to Remain in Equilibrium with the Solid Phase of the Pure Solvent**

The relation dealt with in this article might be considered as the Clausius-Clapeyron equation for solutions. The thermodynamic treatment will be remarkably similar to the case taken up in article 27, which was gone through in somewhat greater detail than will be undertaken here. To fix our ideas for the present, suppose we consider pure water and ice initially in equilibrium at  $0^\circ\text{ C}$ . (The present treatment, however, applies to the equilibrium between two phases of any substance, one of the phases of which contains dissolved material.) Let  $f_1$  represent the specific free energy of the ice,  $f_2$  that of the liquid water. Since the ice and pure water are in equilibrium with each other at  $0^\circ\text{ C}$ , we have

$$f_1 = f_2.$$

Suppose we now add an amount of solute to the pure liquid water sufficient to raise its osmotic pressure from zero to  $\Delta P_o$ . This disturbs the equilibrium between the two phases, and causes the specific free energy  $f_2$  of the solvent to be decreased. Since the two parts of the system have now different specific free energies, a spontaneous change will occur according to inequality 116, tending to decrease the total free energy of the system. The ice, having a higher specific free energy  $f_1$ , will therefore melt and become a liquid having a lower specific free energy  $f_2$ . We see, therefore, that without change of temperature, the ice and water cannot be kept in equilibrium if the amount of solute (and consequently the osmotic pressure  $\Delta P_o$  of the solvent) is changed. To keep the ice and solution in equilibrium and thus to prevent the disappearance of one of the phases, the temperature of the two phases as a whole must be changed by an amount  $\Delta T$ . As is well known, the addition of salt to an ice-and-water mixture lowers its freezing point, which is the equilibrium temperature for the mixture of solution and pure ice.

We now wish to find the relation between the osmotic pressure  $\Delta P_o$  of the solution and the necessary change in temperature  $\Delta T$  in order that the ice and solution may remain in equilibrium. Assume that the temperature is changed from  $T$  to  $T + \Delta T$ . We must recall (from eq. 118) that in order to have equilibrium at the new temperature  $T + \Delta T$  the new free energy of the ice  $f_1$  must equal that of the solution  $f_2$ . That is, both initially and finally we have

$$f_1 = f_2,$$

and therefore

$$df_1 = df_2. \quad (191)$$

The specific free energy of the water in the form of ice depends here only upon the temperature and not explicitly on the pressure, since the system is assumed to be under atmospheric pressure at all times and therefore under a constant hydrostatic pressure. Hence (by eq. 3) we have

$$df_1 = \left( \frac{\partial f_1}{\partial T} \right) dT.$$

With equation 143 this becomes

$$df_1 = -s_1 dT. \quad (192)$$

The specific free energy of the water of the solution, on the other hand, depends not only upon the temperature change  $\Delta T$  but also on the amount of solute present, which we shall here measure by the osmotic pressure of the solution  $\Delta P_o$ . The change in the free energy of the solvent of the solution  $df_2$  therefore depends upon two variables, and (by eq. 3) we have

$$df_2 = \left( \frac{\partial f_2}{\partial P_o} \right)_T dP_o + \left( \frac{\partial f_2}{\partial T} \right)_{P_o} dT.$$

With equations 152 and 143 this becomes

$$df_2 = -v_2 dP_o - s_2 dT. \quad (193)$$

Introducing 192 and 193 into 191 and remembering that  $v_2$  is nothing more than  $v$ , the specific volume of the pure solvent, we have

$$-s_1 dT = -v dP_o - s_2 dT. \quad (194)$$

Rearranging 194, we have

$$\frac{dP_o}{dT} = -\frac{(s_2 - s_1)}{v}. \quad (195)$$

As in article 27,  $(s_2 - s_1)$  gives the change in entropy of the solvent in going isothermally and isobarically from phase 1 to phase 2. We may now write (eq. 84)

$$s_2 - s_1 = \Delta s = \frac{\Delta h}{T} \quad (196)$$

where  $\Delta h$  is the latent heat that must be added per gram in going from the first to the second phase. When we are dealing with ice and water,  $\Delta h$  would be the well-known heat of fusion of ice  $l$ . Inserting 196 in 195 we have

$$\frac{dP_o}{dT} = -\frac{\Delta h}{vT} \quad \text{or} \quad dP_o = -\frac{\Delta h}{vT} dT. \quad (197)$$

In particular for water

$$\frac{dP_o}{dT} = -\frac{l}{vT} \quad \text{or} \quad dP_o = -\left(\frac{l}{vT}\right) dT. \quad (198)$$

For finite changes, 197 and 198 become

$$\Delta P_o = -\left(\frac{\Delta h}{vT}\right) \Delta T \quad (199)$$

and

$$\Delta P_o = -\left(\frac{l}{vT}\right) \Delta T. \quad (200)$$

All the quantities in the parentheses of equation 199 are positive. Whenever, therefore, soluble material, whose amount is measured by the osmotic pressure  $\Delta P_o$  of the solution, is added to a solution, the freezing point of the solution is depressed by the amount ( $-\Delta T$ ).

Equation 199 is quite general and is not restricted to describing equilibria between ice and water. It will, for example, predict how the boiling point of water changes with changes in its content of dissolved material. As a measure of the amount of dissolved material, we can take the osmotic pressure  $\Delta P_o$  of the solution according to equation 226.

By equation 199 we shall show that as the amount of dissolved material in the solution increases, the boiling point of the solution also increases. According to previous conventions, we must take the water vapor as phase 1. The second phase is therefore, as before, the solution. Consequently,  $\Delta h$  will represent the heat that must be added to the water vapor in order to condense it to the liquid phase. This is negative, since actually an amount of heat equal to the heat of vaporization of the water must be removed from the steam to condense it to water at 100° C; that is,  $\Delta h = -540$  calories, or  $-2.27 \times 10^{10}$  ergs per gram. The term  $v$  is the specific volume of the water at 100° C and therefore equals approximately unity in the c.g.s. system. Equation 199 then gives for the osmotic pressure

$$\Delta P_o = \frac{2.27 \times 10^{10}}{1 \times 373} \Delta T \text{ dynes per cm}^2$$

and enables one to calculate the rise in the boiling point of water  $\Delta T$  attendant upon the addition of an amount of dissolved material producing the osmotic pressure  $\Delta P_o$ .

Since by equation 226, the osmotic pressure can be calculated immediately for dilute solutions from the amount of dissolved material, we see that equation 199 at the same time predicts both a decrease of the freezing point and a rise of the boiling point of a solution with increase in the amount of dissolved material.

### 30. Generalized Treatment of the Effect of Pressure on the Freezing Point, and Its Application to Relatively Moist Soils—Generalized Clausius-Clapeyron Equation

Equation 186 gives the change in freezing point  $dT$  caused by a change in hydrostatic pressure  $dP$  on water. The hydrostatic pressure as well as any changes in its value was exerted uniformly on both the phases (ice and water). Under these conditions, the freezing point is lowered  $0.00748^{\circ}\text{C}$  per atmosphere increase of pressure, as is shown later in this article. This is only a special case of the following generalized treatment. We shall now consider the case where the hydrostatic pressure exerted uniformly on the ice differs from that exerted uniformly on the water. As another special case of this, we shall find that the freezing point of water is lowered  $0.0899^{\circ}\text{C}$  per atmosphere increase of pressure on the ice alone, the pressure on the water remaining unchanged. This depression is twelve times as great as that which is observed when the pressure is exerted uniformly on both the water and the ice.

In order to be specific, we derive the following expressions with respect to ice and water, but the results apply equally to the freezing point of any other substance.

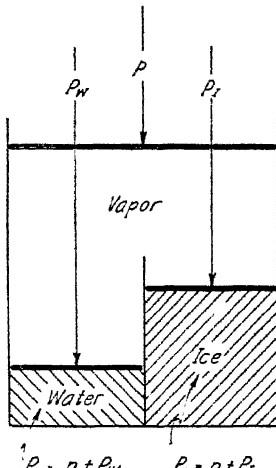
Consider figure 16, in which  $P_I$  represents the pressure exerted uniformly on the ice by a piston that is permeable to water vapor only and  $P_W$  represents the pressure exerted uniformly on the water by a piston that is permeable to water vapor only,  $P_W$  and  $P_I$  being always so related that there is a common vapor pressure  $p$  throughout. This, of course, means that the three phases are always in equilibrium with each other. The total hydrostatic pressures in the water and in the ice are then

$$P_2 = p + P_W,$$

and

$$P_1 = p + P_I,$$

respectively, as indicated in the figure, since the vapor pressure is acting on both the ice and the water. Let  $T$  be the freezing point of the water under these conditions, that is, the temperature at which all three phases are in equilibrium with each other. In the following discussion,  $v_1$ ,  $s_1$ , and



$$P_2 = p + P_W \quad P_1 = p + P_I$$

Fig. 16.—Equilibrium between the solid, liquid, and vapor, when the pressure exerted on each of the three phases may be different.

$f_1$  are quantities associated with the ice phase and  $v_2$ ,  $s_2$ , and  $f_2$  with the liquid phase.

With these pressures, we now seek an expression relating the change in freezing point  $dT$  to a change in any one or all of the pressures. Since we have postulated that the phases are to be in equilibrium, we have (art. 22)

$$f_1 = f_2.$$

This means that when any change occurs in the system, the two free energies must change by an equal amount, namely,

$$df_1 = df_2.$$

In the same manner as with equation 180, we substitute for  $df_1$  and  $df_2$  above and obtain

$$v_1 dP_1 - s_1 dT = v_2 dP_2 - s_2 dT$$

since  $dP_1$  and  $dP_2$  are the total changes in pressure on the ice and water, respectively. Unlike the previous case, these two pressures are in general not now equal to each other. The above equation could, of course, have been obtained immediately from the generalized definition of the differential of the free energy given by equation 97, since no appreciable useful work  $dw_m$  is done in changing the pressures on two such almost incompressible phases as ice and water. Substituting for  $dP_1$  and  $dP_2$  in the above, and dividing through by  $dT$ , we have

$$v_1 \left( \frac{dp}{dT} + \frac{dP_I}{dT} \right) - s_1 = v_2 \left( \frac{dp}{dT} + \frac{dP_W}{dT} \right) - s_2.$$

Rearranging, we have

$$\frac{v_2 dP_W}{dT} - v_1 \frac{dP_I}{dT} + \frac{dp}{dT} (v_2 - v_1) = (s_2 - s_1)$$

and exactly as in obtaining equation 186, we may set

$$s_2 - s_1 = \frac{l}{T},$$

where  $s_2 - s_1$  is the difference in the specific entropies of the two phases in equilibrium with each other and  $l$  is the latent heat of fusion of ice and is positive. We have then

$$\frac{v_2 dP_W}{dT} - v_1 \frac{dP_I}{dT} + \frac{dp}{dT} (v_2 - v_1) = \frac{l}{T}. \quad (201)$$

This equation was first derived by Hudson (80) through an entirely different line of reasoning. He recognized the following four ways in which the freezing point is changed by changes of pressure.

*Case 1. The total change in pressure on the ice is always equal to the total change in pressure on the water.* Consequently,  $dp + dP_w = dp + dP_I$ . Let the total change equal  $dP$ . Equation 201 becomes then

$$\frac{dp + dP_w}{dT} = \frac{dp + dP_I}{dT} = \frac{dP}{dT} = \frac{l}{(v_2 - v_1)T}. \quad (202)$$

This is the special case taken up in article 27. Substitution of the proper values for the specific volume of water,  $v_2$ , and ice,  $v_1$ , and the latent heat of fusion  $l$  from ice to water (the latter is positive as brought out in art. 27), we find that a total increase in pressure  $dP$  equal to 1 atmosphere lowers the freezing temperature by the usual amount  $dT = 0.00748^\circ\text{C}$ .

*Case 2. The pressure on the water remains constant while the pressure on the ice is changed.* Consequently,

$$\frac{dP_w}{dT} = 0,$$

and equation 201 becomes, after dividing through by  $v_1$ ,

$$\frac{dP_I}{dT} = -\frac{l}{Tv_1} - \frac{dp}{dT}\left(1 - \frac{v_2}{v_1}\right). \quad (203)$$

The first term on the right is many thousand times as large as the last term, as may be seen by substituting the proper values for the different terms; hence the last may be neglected, and we have

$$\frac{dP_I}{dT} = -\frac{l}{Tv_1}. \quad (204)$$

Substitution of the proper values in the right side of this shows that an increase in pressure,  $dP_I$  on the ice alone, equal to 1 atmosphere, *lowers* the freezing temperature by the amount  $dT = 0.0899^\circ\text{C}$ , a depression which is twelve times as great as that which is observed in case 1 when the pressure is exerted uniformly on the water and ice.

*Case 3. The pressure on the ice remains constant while the pressure on the water is changed.* Consequently,

$$\frac{dP_I}{dT} = 0,$$

and equation 201 becomes, after dividing through by  $v_2$ ,

$$\frac{dP_w}{dT} = +\frac{l}{Tv_2} + \frac{dp}{dT}\left(\frac{v_1}{v_2} - 1\right);$$

and neglecting the small second term on the right, as was done in case 2, we have

$$\frac{dP_w}{dT} = + \frac{l}{T v_2}. \quad (205)$$

Substitution of the proper values in the right side of this equation shows that an increase in pressure  $dP_w$  on the water alone, equal to 1 atmosphere, raises the freezing temperature by the amount  $dT = 0.0824^\circ\text{C}$ . This is in complete contrast to case 2.

Equation 205 might well describe, for relatively moist but not saturated soils, the relation between  $dP_w$ , the tension in soil moisture (as measured by a tensiometer for example) and  $dT$ , the corresponding freezing-point depression (as determined by the customary Beckmann method) if the soil moisture (under a state of tension depending upon the soil moisture content) is transformed to ice (under atmospheric pressure) upon freezing. This follows because if we have ice and water at equilibrium under atmospheric pressure, then the freezing point will be  $0^\circ\text{C}$ . Now if we change the pressure on the water alone, so that it is under the same tension  $dP_w$  as the soil moisture, then  $dT$ , the freezing-point depression of the system, should be given by equation 205. That the change in the freezing point  $dT$  is negative (indicating a freezing-point depression) is seen immediately from equation 205 when it is recalled that  $dP_w$  (the tension that must be put on the free water to place it in equilibrium with the soil moisture) is negative. A comparison of equation 198 with 205 shows that an osmotic pressure  $dP_o$  will cause the same freezing-point depression  $dT$  as a tension  $dP_w$  in the soil moisture, provided that when the soil moisture freezes to ice, the ice separates out from the soil moisture to a higher pressure of 1 atmosphere.

Schofield (138) gives an equation for calculating the freezing-point depression of soil moisture whose form may be transformed into that of equation 205 when certain suspected typographical errors in his published equation are corrected. He does not give any derivation for it, though, but mentions that the  $pF$  values, calculated from freezing-point depressions, he has plotted in his curve were calculated by means of it.

The total freezing-point depression of any relatively moist normal soil would in this case be the sum of (1) the effect of pressure given by equation 205 and (2) the effect of dissolved material in the soil solution given by equation 198.

*Case 4. The total changes in pressure on the ice and water are always so related that the freezing temperature remains constant.* Consequently,  $dT = 0$  and equation 201 becomes, upon rearrangement,

$$\frac{(dP_I + dp)}{(dP_w + dp)} = \frac{d(P_I + p)}{d(P_w + p)} = \frac{dP_1}{dP_2} = \frac{v_2}{v_1}.$$

Thus if the changes in pressure on the water and ice are inversely proportional to the specific volumes, the freezing temperature will not change.

Let us now illustrate the application of the above four cases by a consideration of several specific examples. Let us first find the freezing temperature of water which is under a pressure of 10 atmospheres when upon freezing it is transformed into ice under a pressure of 16 atmospheres. According to case 1, ice and water are in equilibrium under a uniform pressure of 10 atmospheres at  $-10(0.00748)^\circ\text{C}$ . If a pressure of 6 additional atmospheres be applied to the ice alone, the freezing temperature will, according to case 2, fall an additional  $6(0.0899)$  degrees. The resultant freezing temperature of the system is  $-0.614^\circ\text{C}$ .

But suppose the uniform pressure on the water is 16 atmospheres when its ice is under a pressure of only 10 atmospheres. By case 1, ice and water are again in equilibrium under a uniform pressure of 10 atmospheres at  $-10(0.00748)^\circ\text{C}$ . If now, 6 additional atmospheres be applied to the water alone, the freezing temperature will, by case 3, rise  $6(0.0824)$  degrees and will finally be  $0.420^\circ\text{C}$  above zero.

The use of the four cases may be also illustrated by showing that the lowering of the freezing point of solutions can be considered as the result of osmotic pressure acting as a negative pressure tending to expand the water. At first, this seems strange. It is known that ordinarily a positive pressure lowers the freezing temperature of water and a negative pressure raises the freezing temperature; therefore it might seem that solutions should freeze above  $0^\circ\text{C}$  rather than below, if the dissolved material produces a tension. As has been pointed out by Hudson (80), this reasoning is not correct, because the ice which freezes from a solution is under atmospheric pressure, not negative pressure; and only the solution may be properly regarded as being under a negative pressure, caused by the dissolved substance. Both the ice and solution are, of course, under atmospheric pressure, but in the case of the solution, the dissolved substance in effect contributes an additional negative pressure to the water. Let us assume that the dissolved material has the same tendency to expand that part of the solvent containing the dissolved material as the molecules of a perfect gas have to expand the volume they occupy. This might be thought of as causing a tension  $-P_w$  in the water of the solution tending to pull it apart, and determined by  $P_{w^e} = x_2 RT$  where  $x_2$  is the mol fraction of the solute in the solution. (This is recognized to be nothing more than the ideal gas law where  $R$  is the gas constant per gram.) Since this falls under case 3, let us substitute this expression for  $-P_w$  for that in the expression under case 3 and obtain, after rearrangement,

$$dT = - \frac{RT^2}{l} dx_2 = - \frac{RT^2}{l} x_2,$$

since  $dx_2$  is measured with respect to the pure solvent. This is the same as the well-known relation that van't Hoff obtained for the freezing-point depression,  $dT$ , produced by the addition of an amount of solute  $dx_2$ , according to article 38. From the agreement of these two expressions for the molecular depression of the freezing temperatures, we must conclude that solutions may be regarded as being under a negative pressure, comparable with a positive mechanical tension, this negative pressure being caused by the dissolved substance and being numerically identical with the osmotic pressure of the solution.

Let us consider another illustration. As pointed out under case 4, it is possible to apply pressure to the ice and water in such a way as not to change the freezing point of the water. We had

$$\frac{dP_1}{dP_2} = \frac{v_2}{v_1}.$$

The specific volume of ice is  $v_2 = 1.0909$ , and of water,  $v_1 = 1.0001$  cc per gram, respectively. Thus

$$\frac{dP_1}{dP_2} = 1.09,$$

so that the freezing temperature of the water will always remain the same no matter what pressure is applied to it so long as the pressure applied to it is 9 per cent greater than that simultaneously applied to the ice.

Finally, although it has never, so far as is known, been pointed out, it seems that freezing according to case 3 might occur in the freezing of soil moisture in the soil during winter. Of course, if as pointed out previously under case 3, the ice (freezing out from the relatively moist soil) separates out from the soil moisture to a pressure of 1 atmosphere, then this case must always occur. Suppose in a soil cavity some distance above a water table, we have an isolated particle of ice; and suppose also that below this cavity and extending down to the water table are capillary columns of water. Since the water in the capillaries is under tension, it will, at 0° C, have a lower vapor pressure than the particle of ice. Consequently, the moisture system in the cavity will not be at equilibrium at that temperature, and the ice will distill over to the water in the capillaries. The temperature of equilibrium may be calculated as follows: the water in the capillaries leading up to the cavity is under a tension that is less than atmospheric by an amount given by the height of the capillaries according to article 42. If, for the sake of our present argument, we assume that the water table is  $76 \times 13.6$  centimeters below the cavity and that all the soil capillaries are small enough to raise the water this high, then the

hydrostatic pressure in the water at the upper end of the soil capillaries having their terminals in the cavity is  $-76 \times 13.6$  grams, or minus 1 atmosphere. At  $0^\circ\text{C}$ , if the water in the soil capillaries were not under tension, it would be in equilibrium with the isolated particle of ice in the cavity and would freeze at  $0^\circ\text{C}$ ; however, in our present case, we must consider the pressure on the particle of ice in the cavity as remaining constant, whereas the pressure on the capillary water adjacent to the cavity has been decreased by 1 atmosphere. Thus, according to case 3, the ice-particle-soil-moisture system in the cavity will be in equilibrium at  $-0.0824^\circ\text{C}$ , at which temperature that part of the soil moisture adjacent to the cavity which is under a tension of 1 atmosphere will begin to freeze. That is, the freezing point of the soil moisture which is under a tension of 1 atmosphere is in the present case  $-0.0824^\circ\text{C}$ , since the particle of ice is isolated from the water; and not  $+0.00748^\circ\text{C}$ , as might at first have been expected if case 1 had inadvertently been applied under the assumption that the ice was attached to the water and both were under the same pressure. In general, if the soil capillaries are small enough and the cavity containing the isolated particle of ice is  $h$  centimeters above the water table, the freezing temperature of the moisture adjacent to the soil cavity is

$$h \left( \frac{0.0824}{76 \times 13.6} \right) \text{ degrees below } 0^\circ\text{C}.$$

Freezing according to case 3 might also occur in the freezing of soils when the Beckmann technique is used at relatively high soil moisture contents.

### 31. Dependence of the Free Energy of a Solvent $\Delta f$ on the Amount of Dissolved Material as Measured by Its Freezing-Point Depression $\Delta T$

As will be recalled (eq. 151), the free energy  $\Delta f$  of a liquid having an osmotic pressure  $\Delta P_o$  is given by

$$\Delta f = -v \Delta P_o, \quad (206)$$

where  $v$  denotes the specific volume of the pure solvent. Substituting equation 199 into 206, we have

$$\Delta f = \frac{\Delta h}{T} \Delta T,$$

which expresses the free energy  $\Delta f$  of a solution with respect to that of the pure solvent due to the presence of dissolved material in it, in terms of its freezing-point depression  $\Delta T$ . For water, let us use the more customary

symbol  $l$  in place of  $\Delta h$  for the latent heat of transition from one phase to the other; we then have

$$\Delta f = \frac{l}{T} \Delta T. \quad (207)$$

Although for concreteness in the derivation we have considered the transition between a water solution and ice, these equations are perfectly general and apply to any solution in equilibrium with another phase of one of its components in the pure state.

Equation 189 for the free energy due to hydrostatic pressure resembles 207 for the free energy due to osmotic pressure. Both express  $\Delta f$  in terms of the freezing-point depression  $\Delta T$ ; but 189 contains  $\Delta v$  and  $v$ , the expansion of the liquid upon freezing and its specific volume respectively, whereas 207 contains neither.

### 32. Dependence of the Free Energy of a Liquid Surface Possessing a Surface Tension $\sigma$ on Its Area $A$

As will be recalled from elementary physics, the surface tension  $\sigma$  of a liquid is defined as the tensional force in dynes per unit of length of the film measured, the tensional force being measured in a direction normal to the unit of length in the film. Thus if we increase the area of the film by an amount  $dA$ , the work done on the system composed of the vapor-liquid interface of area  $A$  will have been  $\sigma dA$ . As will be noticed, surface tension can be expressed either as dynes per centimeter or as ergs per square centimeter. In either case, the dimensions of surface tension will be seen to be the same.

Now the mechanical work done on a system at constant temperature, excluding the work of expansion against a pressure  $P$ , has been found to equal the increase of the free energy of the system according to equation 99. Thus the increase in the total free energy of a liquid surface  $A$  when its area is increased by the amount  $\Delta A$  is given by

$$\Delta F = \sigma \Delta A. \quad (208)$$

Since, however, by convention the free energy  $\Delta f$  should refer to the energy per gram of the water and since equation 208 as it stands refers to the total free energy  $\Delta F$  of an element of surface  $\Delta A$ , we must change the above equation. If we let  $\tau$  represent the thickness of the surface layer of water in which the properties are different from the main body of the liquid, then the average of free energy per gram throughout the liquid surface layer may be represented by

$$\Delta f = \frac{\sigma}{\tau \rho}, \quad (209)$$

where  $\rho$  represents the average density of the water in the layer of thickness  $\tau$ .

As will be shown (art. 46), the total specific surface energy is always greater than the surface tension  $\sigma$  or the total free energy  $\Delta F$  per unit area as given by equation 208.

### 33. Dependence of the Free Energy of a Liquid on Its Surface Tension and Its Radius of Curvature

As will be shown (eq. 272), we have for the vapor pressure  $p$  over a curved vapor-liquid interface whose radius of curvature is  $r$ , where the vapor pressure over the free water is  $p_0$  and where the surface tension is  $\sigma$ , the equation

$$\ln \frac{p}{p_0} = \frac{v}{RT} \frac{2\sigma}{r}. \quad (210)$$

From equation 159 we have then for the free energy of the vapor above, or of the liquid below the curved vapor-liquid interface

$$\Delta f = RT \ln \frac{p}{p_0} = \frac{2\sigma v}{r} \quad (211)$$

where  $v$ , the specific volume, is unity for water in the c.g.s. system and where the sign of  $r$  is negative if the vapor-water interface is concave to the vapor as is true for soil moisture. If we are dealing with water droplets,  $r$  is positive, and equation 210 predicts an increase in the vapor pressure  $p$  over that of the vapor pressure  $p_0$  of the datum, which we have taken as free, pure water.

### 34. Dependence of the Free Energy of the Solvent of a Solution on the Amount of Dissolved Material Present

Raoult's law applies to the solvent in a dilute solution and states that its vapor pressure  $p$  is proportional to its mol fraction  $x$ . That is,

$$p = cx, \quad (212)$$

where  $c$  is the constant of proportionality. We wish to express 212 in terms of free energy  $f$  rather than of vapor pressure  $p$ .

Consider  $x$  and  $x_0$ , two mol fractions of the solvent. These will determine two different equations of the type 212. Dividing one of these by the other and taking the logarithm of both sides, we have

$$\ln \frac{p}{p_0} = \ln \frac{x}{x_0}. \quad (213)$$

Multiplying both sides of equation 213 by  $RT$ , we have (eq. 159 and art. 22) for the free energy  $\Delta f$  of the solvent at one mol fraction  $x$ , expressed in terms of its value at the other mol fraction  $x_0$ , the equation

$$\Delta f = (f - f_0) = RT \ln \frac{p}{p_0} = RT \ln \frac{x}{x_0}, \quad (214)$$

where it is assumed that the behavior of the vapor of the solvent approximates that of the ideal gas. Suppose that  $p_0$  refers to the vapor pressure of the pure solvent. Then  $x_0$  will be the mol fraction of the pure solvent. That is, by the usual definition of the mol fraction,  $x_0 = 1$  exactly. From equation 214 we can then write

$$f = f_0 + RT \ln x, \quad (215)$$

where  $f_0$  now equals the free energy of the free, pure solvent, which by our previous conventions is our datum, or zero point of free energy for a liquid. Since  $f_0$ , the free energy of the datum, is a constant, equation 215 becomes by differentiation, where  $p$  and  $T$  are held constant,

$$\left( \frac{df}{dx} \right)_{pT} = \frac{RT}{x}. \quad (216)$$

As we shall wish to distinguish between the mol fraction of the solvent and of the solute in later discussions, we shall let  $x_1$  represent the mol fraction of the solvent and  $x_2$  that of the solute. Hence in the equation above,  $x$  will be changed into  $x_1$ . Since, presumably, we are dealing with a dilute solution, the mol fraction  $x_1$  of the solvent must be very close to unity. We see this because if  $m_1$  is the number of mols of the solvent and  $m_2$  the number of mols of the solute present in the solution, then the mol fraction  $x_1$  of the solvent is defined by

$$x_1 = \frac{m_1}{m_1 + m_2}. \quad (217)$$

If the concentration of the solution is low,  $m_2$  must also be small in equation 217. The mol fraction  $x_1$  of the solvent is therefore equal approximately to unity in a dilute solution. Such an approximation can be made in equation 216 without altering it appreciably; and 216 therefore becomes

$$\left( \frac{\partial f_1}{\partial x_1} \right)_{pT} = RT, \quad (218)$$

where the subscripts  $pT$  have been added merely as a reminder that the temperature and external pressure are to be kept constant during all changes of concentration in these solutions. Equation 218 gives the dependence of the free energy of the solvent  $f_1$  on its mol fraction  $x_1$ .

For future use, we shall also wish to express the changes in the free energy of the solvent  $f_1$  in terms of changes in the mol fraction of the solute  $x_2$ . To do this let us first recall that for a binary solution,

$$x_1 = \frac{m_1}{m_1 + m_2}$$

and

$$x_2 = \frac{m_2}{m_1 + m_2};$$

therefore

$$x_1 + x_2 = 1. \quad (219)$$

Differentiating 219, we find

$$dx_1 = -dx_2. \quad (220)$$

Inserting 220 into 218

$$\left( \frac{\partial f_1}{\partial x_2} \right)_{pT} = -RT. \quad (221)$$

Equations 218 and 221 are merely two other ways of stating Raoult's law in terms of free energy rather than vapor pressure. Equation 221 states, by the way, that as the weight fraction  $x_2$  of the solute increases (that is, as the solution becomes more concentrated) the free energy  $f_1$  of the solvent decreases. Equation 218, on the other hand, states that as the proportion of solvent  $x_1$  increases, the escaping tendency, or free energy  $f_1$ , of the solvent increases. These two expressions will become useful in later considerations.

For finite changes equation 221 may be written

$$\Delta f_1 = -RTx_2. \quad (222)$$

Equation 222 gives the free energy  $\Delta f_1$  of the solvent of a solution with respect to that of the free, pure solvent, which we have taken as the datum or zero point of free energy. As the amount of dissolved material  $x_2$  continues to increase, the free energy of the solvent  $\Delta f_1$  continues to decrease.

### 35. Dependence of the Osmotic Pressure of a Solution on the Amount of Solute Present—Van't Hoff's Law of Osmotic Pressure

As has been shown (eq. 221), the absolute free energy  $f_1$  of a solvent is always decreased by the addition of a solute at constant temperature and pressure. By the application of a pressure  $\Delta P$  to the solution, however, the free energy of the solvent can be restored to its value in the pure state. The hydrostatic pressure  $\Delta P$  that must be applied to the solution in order to place it in equilibrium with the pure solvent has been defined in article 24 as the osmotic pressure  $\Delta P_o$  of the solution.

In general, since the absolute free energy  $f_1$  of the solvent of a solution depends both on the hydrostatic pressure and on the mol fraction of solute present, and since  $df_1$  is a perfect differential (art. 1), we have

$$df_1 = \left( \frac{\partial f_1}{\partial P} \right)_{x_2 T} dP + \left( \frac{\partial f_1}{\partial x_2} \right)_{PT} dx_2, \quad (223)$$

where the temperature is assumed to remain constant. Suppose that as the mol fraction of solute  $x_2$  in the solution is varied, the hydrostatic pressure  $P$  on the solution is so adjusted as always to keep the absolute free energy  $f_1$  of the solvent the same as that of the free, pure solvent. We then have  $df_1 = 0$  in equation 223, which now becomes

$$\left( \frac{\partial f_1}{\partial P} \right)_{x_2 T} dP + \left( \frac{\partial f_1}{\partial x_2} \right)_{PT} dx_2 = 0. \quad (224)$$

Substituting equations 157 and 221 into 224, we have

$$vdP - RT dx_2 = 0,$$

or

$$\frac{dP}{dx_2} = \frac{RT}{v}. \quad (225)$$

If  $x_2$  represents the total mol fraction of all dissolved material of the solute present, this equation becomes

$$\Delta P = \frac{RT}{v} x_2.$$

As was mentioned at the beginning of this article, the  $\Delta P$  is equal to the osmotic pressure  $\Delta P_o$ ; and we have, accordingly,

$$\Delta P_o = \frac{RT}{v} x_2. \quad (226)$$

This is a statement of van't Hoff's law. Equation 226 thus gives the osmotic pressure  $\Delta P_o$  of a dilute solution in terms of the amount of solute present, expressed in terms of its mol fraction  $x_2$ .

### 36. Dependence of the Vapor Pressure of the Solvent of a Solution on the Amount of Dissolved Material Present

Let us assume that we start out with a free, pure solvent whose vapor pressure is  $p_0$ . If we add an amount of dissolved material whose value is given by the mol fraction  $x_2$ , the vapor pressure of the solvent will be lowered to  $p$ . By equation 159 and article 22, the free energy of the solvent of the solution expressed in terms of the vapor pressures is given by

$$\Delta f_1 = RT \ln \frac{p}{p_0}; \quad (227)$$

and in terms of the mol fraction of dissolved material  $x_2$  according to equation 222 it is

$$\Delta f_1 = -RT x_2. \quad (228)$$

Equating 227 and 228 and solving for the vapor pressure of the solvent of the solution, we have for dilute solutions

$$p = p_0 e^{-x_2} \quad (229)$$

showing the dependence of the vapor pressure  $p$  of the solvent of a dilute solution on the mol fraction of solute present  $x_2$  when the vapor pressure of the pure solvent is  $p_0$ .

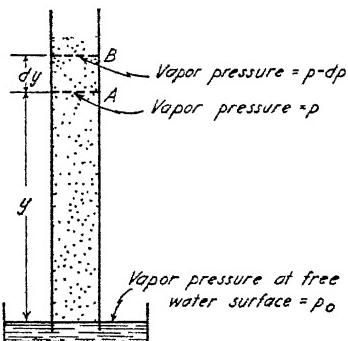


Fig. 17.—Column of vapor in an attractive force field.

### 37. Dependence of Atmospheric Pressure on Height

Consider a vertical column of air of unit cross-sectional area and unlimited height in the earth's gravitational field. We wish to find the relation between the height  $y$  and the gas pressure  $p$  in the chamber of figure 17. Sometimes this relation is called Laplace's law of atmospheric pressure. It applies equally well, however, to the variation of vapor pressure with height above a free liquid surface, as, for example, water, when the whole system has come to equilibrium at the same temperature, in a uniform gravitational field. We shall use the following notation:

$p$  = pressure in dynes per square centimeter at a distance  $y$  above the reference point, for example, the surface of the earth or a free water surface

$v$  = volume of the air

$\rho$  = density of air in grams per cubic centimeter

$g$  = 980 dynes per gram, the gravitational constant

$R$  = gas constant per gram defined by the well-known gas law,  
 $pv = RT$

Transforming, we have

$$p = \rho RT,$$

and finally

$$\rho = \frac{p}{RT}. \quad (230)$$

The pressure at *A* is greater than that at *B* by an amount equal to the weight of the section *dy* of the column of gas or vapor  $\rho g dy$ . That is, in going from *A* to *B*, the pressure changes by the amount  $-dp$ . This is our basic assumption in deriving Laplace's pressure law and is quantitatively stated by

$$-dp = \rho g dy. \quad (231)$$

Eliminating  $\rho$  in equation 231 by means of equation 230 and rearranging, we have

$$-\frac{dp}{p} = \frac{g}{RT} dy.$$

Integrating from  $y = 0$  at the surface of the free water, where  $p = p_0$ , to  $y = y$ , where  $p = p$ , we have

$$\ln p \Big|_{p_0}^p = -\frac{g}{RT} y \Big|_0^y$$

$$\ln \frac{p}{p_0} = -\frac{g}{RT} y. \quad (232)$$

Thus if we know the vapor pressure  $p_0$  at the free-water surface where  $y = 0$ , equation 232 determines the pressure  $p$  at a height  $y$ . Transforming 232 into a form that expresses  $p$  explicitly in terms of  $y$  and  $T$ , we have

$$p = p_0 e^{-\frac{gy}{RT}} \quad (233)$$

which is a statement of Laplace's law of atmospheric pressure.

### 38. Dependence of the Freezing Point of a Dilute Solution on the Mol Fraction of Solute Present

The free energy of the solvent of a dilute solution expressed in terms of the mol fraction of solute present  $x_2$  is (eq. 222)

$$\Delta f_1 = -RT x_2; \quad (234)$$

and in terms of the change in freezing point of the solution  $\Delta T$ , it is (eq. 207)

$$\Delta f_1 = \frac{l \Delta T}{T}. \quad (235)$$

Equating 234 to 235, we have

$$\Delta T = - \frac{RT^2}{l} x_2$$

showing that the freezing point of the solution is lowered by an amount  $-\Delta T$  by the mol fraction of dissolved material  $x_2$ .

### 39. A Datum for Free Energy and the Dependence of the Latter on Vapor Pressure

As will later be evident (art. 73), the absolute free energy  $f$  of soil moisture is not zero except at 0° A. Generally, however, it is convenient to choose a body of pure water outside the influence of any adsorptive field as the zero point of reference or datum with respect to which the free energy of other bodies of water are measured. Thus any water under the conditions corresponding to the datum is said to have its free energy  $\Delta f$  equal to zero although its absolute free energy  $f$  is by no means equal to zero.

Since we are interested in free-energy changes occurring at constant temperature, the temperature of the datum is usually taken to be the same as that of the soil moisture. Since the moisture is situated in a gravitational field, it has free energy due to its position. The free energy of any soil moisture due to its presence in the gravitational field is measured with respect to the level of the datum. Thus when the soil moisture is situated at the same level as the datum, its free energy due to its position in the gravitational field is zero.

Under usual conditions the atmosphere exerts on the soil moisture a pressure either greater or less than 1 standard atmosphere. This pressure contributes to the total free energy of the soil moisture (art. 25). Since this pressure, being exerted on both the datum and the unknown, is common to both, it is usually neglected. Thus we speak of the freezing point of pure water as 0° C with the understanding that it is under a pressure of 1 atmosphere. If we could reduce the pressure to zero, we should actually have a freezing point of +0.0073° C (art. 30 and eq. 378). All pressures on soil moisture are therefore measured with respect to the pressure on the datum. If, for example, the atmospheric pressure on the datum is 0.9 atmospheres and that on the soil moisture 1.1 atmospheres, the free energy  $\Delta f$  on the soil moisture due to hydrostatic pressure will be taken as that produced by only 0.2 of an atmosphere.

Thus we shall always associate arbitrarily the following conditions with our datum, or zero point, for the free energy of soil moisture:

1. It will usually have the same temperature as the water or soil moisture whose free energy we wish to determine.

2. Free energy of the datum due to its position in the gravitational field will be arbitrarily taken as zero, and the free energy of all other bodies due to their presence in a gravitational field will be measured with respect to the datum according to article 26.

3. If, as is usually the case, there is a pressure exerted on the datum, this value will be arbitrarily taken as the zero point of pressure in calculating the free energy due to pressure.

4. The datum is assumed to be free of all extraneous fields, such as adsorptive force fields surrounding soil particles, except gravitation, but is taken to include the usual surface forces next to a free flat water surface.

Under these conditions, water which is taken as the datum will for brevity be called merely "free water."

It frequently happens that we wish to determine the free energy of a substance in a particular state, such as solid or liquid, yet the conditions determining its free energy in the particular phase are so complicated that we cannot calculate its free energy directly. For example, the free energy of liquid soil moisture is, in general, determined by the amount of dissolved material, by the hydrostatic pressure in the soil moisture, and by the strength and distribution of the adsorptive force field that surrounds the elementary soil particles and acts on the soil moisture. Often it is impossible to calculate directly the contribution of each of these factors to the total free energy and, consequently, to calculate the total free energy of the soil moisture.

One way out of this difficulty is to use the results of article 22. We there found that when two or more phases of the same substance are in equilibrium with each other, then the specific free energies of all the phases are alike. Consequently, if we can find another phase whose free energy can be more easily calculated, and which is in equilibrium with the first phase, we can take the free energy of the second to be also that of the first. If, for example, we wish to ascertain the free energy of the soil moisture in a soil at a particular soil-moisture content, we have merely to determine the free energy of the vapor in equilibrium with it.

The total specific free energy  $\Delta f$  of the vapor, assuming that it behaves as an ideal gas, is given (eq. 159) by

$$\Delta f = RT \ln \frac{p}{p_0}, \quad (236)$$

where  $p$  denotes the vapor pressure of the soil moisture and  $p_0$  denotes the vapor pressure of our datum, or zero point, which for soil moisture we usually take as free, pure water at the same temperature as the vapor whose free energy we wish to determine. Thus, from the simple measure-

ments of the vapor pressures, we can calculate by equation 236 the free energy of a complicated system of soil moisture, measured with respect to the free energy of free, pure water. This fact further emphasizes the general usefulness of the free-energy function in dealing with the energy states of soil moisture.

#### 40. Relation between the Hydrostatic Pressure and Osmotic Pressure of a Pure Solvent and a Solution When the Two Are at Equilibrium

Suppose we have pure water in equilibrium with a soil solution through a semipermeable membrane. Because of the presence of dissolved material in the soil solution, its vapor pressure as well as its free energy will

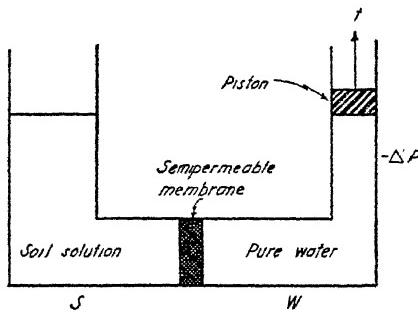


Fig. 18.—Equilibrium of a soil solution with pure water through a semipermeable membrane.

be less than that of the free, pure water. If the proper tension could be placed on the pure water, its vapor pressure as well as free energy would become equal to that of the soil solution. For example, a tension  $t$  might be placed upon the piston in figure 18, such that the vapor pressure and free energy of the pure water would be reduced to those of the soil solution.

In other words, the pure water on the side  $W$  under a hydrostatic pressure  $-ΔP$  can be in equilibrium through a semipermeable membrane with a solution on the side  $S$  having an osmotic pressure  $+ΔP$ . For this reason, past measurements of what has been called the "capillary potential" of soil moisture, which depend upon balancing a column of pure water under tension against the pull of the soil moisture, are open to question. Sometimes, for example, a porous bulb connected to a manometer is immersed in a moist soil whose capillary potential is to be measured. The tension recorded by the manometer is then taken as the capillary potential of the soil moisture, which always contains varying amounts of dissolved material. The concentration of solutes inside the bulb at the

time of measurement is less than the concentration of the soil solution. One wonders whether the tension usually recorded is not, therefore, a combination of the true capillary potential plus the osmotic potential, rather than just the capillary potential alone. Only when the water in the porous bulb immersed in the moist soil and that in the manometer contain the same concentration of dissolved material as the soil solution could the tension indicated by the manometer be considered an accurate measure of the so-called capillary potential in the soil. The establishment of this equality of concentration takes a long time since diffusion of solutes through porous material is extremely slow. The discrepancy between the true capillary potential and what is actually measured decreases as the salinity of the soil solution decreases.

Let us now determine quantitatively the relation between the osmotic pressure  $\Delta P_o$  of a solution in equilibrium with a body of pure water under a hydrostatic pressure  $\Delta P_P$ . The hydrostatic pressure may be negative, in which case it is often called a "tension."

The free energy  $\Delta f_o$  of a solution measured with respect to free, pure water taken as the datum is (eq. 151)

$$\Delta f_o = -v\Delta P_o$$

where  $v$  is the specific volume of the solvent. The free energy due to hydrostatic pressure  $\Delta f_P$ , measured with respect to the same reference point or datum as for  $\Delta f_o$ , of a body of pure water under hydrostatic pressure  $\Delta P_P$  is (eq. 156)

$$\Delta f_P = v \Delta P_P .$$

At equilibrium the free energies of the two bodies must be equal (art. 22); and we have

$$\Delta f_P = \Delta f_o ;$$

therefore

$$\Delta P_P = -\Delta P_o . \quad (237)$$

Now, a minus  $\Delta P_P$  is to be interpreted as a tension. When, therefore, pure water is in equilibrium with a free solution through a semipermeable membrane, the osmotic pressure of the solution  $\Delta P_o$  is numerically equal to the tension ( $-\Delta P_P$ ) in the pure water.

#### 41. Dependence of the Vapor Pressure of a Liquid on the Hydrostatic Pressure in the Liquid

Frequently the vapor pressure of a liquid has been considered with the liquid in contact with the vapor, so that the hydrostatic pressure in the liquid is just equal to the vapor pressure. A solid or a liquid can, however,

exist under a hydrostatic pressure very different from its own vapor pressure. Water, for example, may be held in capillaries under a considerable negative hydrostatic pressure (that is, under tension); yet its vapor pressure is a finite positive quantity. Also water and its vapor may be enclosed in a chamber containing considerable quantities of some inert insoluble gas. The total hydrostatic pressure in the water is then the combined sum of its own vapor pressure and that of the inert gas. Certainly it would seem that the normal vapor pressure of the liquid would be changed by placing the liquid under a state of either tension or pressure. By the "normal vapor pressure of a liquid" we mean its value when we consider a large, free, isolated body of the liquid and its vapor, unaffected by extraneous forces.

We now wish to determine quantitatively how a change in vapor pressure  $\Delta p$  depends on the change of the hydrostatic pressure  $\Delta P$  in the liquid. To fix our ideas, let us consider figure 19. Water at the point *A* in the capillary tube is under a tension or negative hydrostatic pressure determined by the height *h* of the meniscus above the water level in *C*. In equilibrium with the water at *A* is the water vapor enclosed in the chamber *V*. We wish to find how the vapor pressure in *V* is modified by changing the tension on the water at *A*—that is, by increasing or decreasing the length *h* of the capillary column.

Suppose the system comes to equilibrium at constant temperature. Then the vapor pressure *p* will differ from the hydrostatic pressure *P* at *A* except in the limit where *h* equals zero. If the hydrostatic pressure of the liquid at *A* is decreased by increasing *h*, the escaping tendency of the liquid is also decreased. To re-establish equilibrium, therefore, the escaping tendency from the vapor phase must also be decreased by a like amount until its escaping tendency is the same as that from the liquid.

The absolute free energy  $f_L$  of the liquid and  $f_V$  of the vapor are exact measures of their respective escaping tendencies. If the system is originally in equilibrium, then  $f_L = f_V$  (art. 22). If the hydrostatic pressure *P* is changed by an amount  $\Delta P$  and if the system is again allowed to come to equilibrium, the vapor pressure *p* will change by an amount  $\Delta p$ , and the free energies will spontaneously adjust themselves so that

$$\Delta f_V = \Delta f_L.$$

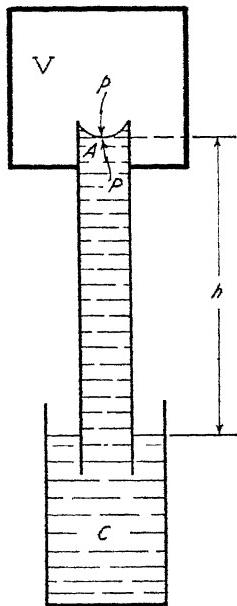


Fig. 19.—Equilibrium of a vapor with the liquid through a curved vapor-liquid interface.

Now (eq. 156)

$$\Delta f_V = v_V \Delta p$$

and likewise

$$\Delta f_L = v_L \Delta P,$$

where  $v_V$  and  $v_L$  are the specific volumes of the vapor and liquid respectively. Since the new state is also an equilibrium state, we may write in differential form

$$v_V dp = v_L dP$$

or

$$\frac{dp}{dP} = \frac{v_L}{v_V}. \quad (238)$$

Since the changes of pressure have been assumed to take place so that the initial and final temperatures are the same, we should write for 238

$$\left( \frac{dp}{dP} \right)_T = \frac{v_L}{v_V}. \quad (239)$$

The fraction  $\frac{v_L}{v_V}$  is, in general, very small. For example, if we consider saturated water vapor and water at 0° C according to the critical tables,  $\frac{v_L}{v_V} = 5 \times 10^{-6}$ . Thus if the hydrostatic pressure on water at 0° C were changed so that  $\Delta P = 20$  atmospheres, equation 239 shows that the vapor pressure would change only by the amount  $\Delta p = 10^{-4}$  atmospheres, approximately. We thus see that the effect of the hydrostatic pressure exerted by the vapor of a liquid on the liquid itself is negligible.

Equation 239 holds not only when the hydrostatic pressure is positive but also when it is negative. If, as in the original case, the liquid is placed under tension,  $dP$  is negative. This means that the change in vapor pressure  $dp$  must also be negative. Thus, increases of hydrostatic pressure  $dP$  cause increases of the vapor pressure  $dp$ , while decreases of hydrostatic pressure ( $-dP$ ) cause decreases in the vapor pressure ( $-dp$ ). As will be recalled, in studies of soil moisture the term "hydrostatic pressure" is not confined to positive pressures, as in engineering, but includes negative pressures also.

Suppose we wished to deal with the effect of very great changes of hydrostatic pressure  $\Delta P$  on the changes of vapor pressure  $\Delta p$  or wished to determine the relation between  $p$  and  $P$  very accurately. Then, if we are dealing with water, for example, we may use Callendar's empirical equation of state for water vapor, which is

$$v_V = 4.548 \frac{T}{p} - 26.3 \left( \frac{373}{T} \right)^{\frac{10}{3}} + 1.0, \quad (240)$$

where  $p$  is the vapor pressure in atmospheres,  $T$  the absolute temperature, and  $v_L$  the specific volume of the vapor. For liquid water we have, likewise, the empirical equation

$$v_L = 1.002(1 - 4.0 \times 10^{-5} P) \quad (241)$$

where  $v_L$  is the specific volume of the liquid water and  $P$  is the hydrostatic pressure.

Of course equation 239 will give immediately the relation between changes of hydrostatic pressure  $\Delta P$  and vapor pressure  $\Delta p$ , especially when the changes are small. It may be desirable, however, to deal with great changes of pressure—for example, several hundred atmospheres. In such a case one may modify the approach as follows by using the two equations 240 and 241 together with 239. We then have

$$\left\{ 4.548 \frac{T}{p} - 26.3 \left( \frac{373}{T} \right)^{\frac{10}{3}} + 1.0 \right\} dp = 1.002(1 - 4.0 \times 10^{-5} P)dP. \quad (242)$$

We shall assume that initially the vapor pressure is  $p_0$  and that this causes a hydrostatic pressure, also  $p_0$ , in the liquid. Finally, the hydrostatic pressure in the liquid is raised to an amount  $P$ , which is very great with respect to  $p_0$ . We can therefore assume that the hydrostatic pressure finally is merely  $P$ . We shall then wish to calculate the resulting vapor pressure  $p$  caused by the hydrostatic pressure  $P$  according to equation 242 above. Integrating 242 above and substituting the limits, we have

$$4.548T \ln \frac{p}{p_0} + \left[ 1 - 26.3 \left( \frac{373}{T} \right)^{\frac{10}{3}} \right] (p - p_0) = 1.002P - 2.004 \times 10^{-5} P^2 \quad (243)$$

or, changing to common logarithms, we have

$$10.46T \log \frac{p}{p_0} + \left[ 1 - 26.3 \left( \frac{373}{T} \right)^{\frac{10}{3}} \right] (p - p_0) = 1.002P - 2.004 \times 10^{-5} P^2. \quad (244)$$

Equation 244 serves to determine the vapor pressure of water  $p$  for any hydrostatic pressure  $P$ , the normal vapor pressure  $p_0$  of free water at the temperature  $T$  of course being known. For example, a solution of the equation above for  $P = 300$  atmospheres and a temperature of  $20^\circ C$  gives an increase of the vapor pressure  $p$ , above its normal value over a free water surface, of only 20 per cent.

We may considerably simplify equation 243 by measuring  $p$  with respect to the normal vapor pressure  $p_0$ , while sacrificing some accuracy.

Let us therefore express 243 in terms of  $\Delta p$  rather than  $p$  and  $p_0$ . Let us place

$$p = p_0 + \Delta p. \quad (245)$$

The logarithmic term of equation 243 then becomes

$$\ln\left(\frac{p_0 + \Delta p}{p_0}\right) = \ln\left(1 + \frac{\Delta p}{p_0}\right). \quad (246)$$

The general series expansion of this logarithm, as obtained from any book of mathematical formulas, is

$$\ln(1 + x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4}$$

or

$$\ln\left(1 + \frac{\Delta p}{p_0}\right) = \left(\frac{\Delta p}{p_0}\right) - \frac{1}{2}\left(\frac{\Delta p}{p_0}\right)^2 + \frac{1}{3}\left(\frac{\Delta p}{p_0}\right)^3 - \dots$$

As previously indicated, even at such great hydrostatic pressures as 300 atmospheres  $\Delta p$  is only 20 per cent of  $p_0$ . We are, therefore, in general, quite justified in dropping all but the first term in the series expansion above and accordingly have

$$\ln\left(1 + \frac{\Delta p}{p_0}\right) = \frac{\Delta p}{p_0}. \quad (247)$$

Introducing equation 247 into 243, recalling that  $(p - p_0)$  equals  $\Delta p$ , and solving for  $\Delta p$  we have

$$\Delta p = \frac{1.002(P - 2 \times 10^{-5}P^2)}{\frac{4.548 T}{p_0} + \left[1 - 26.3\left(\frac{373}{T}\right)^{\frac{10}{3}}\right]}. \quad (248)$$

It is clear that the hydrostatic pressure  $P$  is applied to the liquid only, and not to the vapor.

This equation gives the increase in vapor pressure of water  $\Delta p$ , in atmospheres, corresponding to the application of a hydrostatic pressure of  $P$  atmospheres, the normal vapor pressure  $p_0$  of free water at the temperature  $T$  of course being known. It shows the same relation between hydrostatic pressure and vapor pressure as the more general equation 239. Equation 248 is more useful for water, however, because the two specific volumes have been eliminated by expressing them in terms of the temperature and of the normal vapor pressure of water. Also, equation 248 is more accurate because it takes into account the variation in the

specific volumes with change of hydrostatic pressure. For great hydrostatic pressures it should be used; but for those usually encountered, equation 239 is probably preferable.

Assuming that  $P = 20$  atmospheres and that  $T = 27^\circ \text{C}$ , which makes  $p_0 = 0.035$  atmospheres, we have

$$\begin{aligned}\Delta p &= \frac{1.002(20 - 2 \times 10^{-5} \times 20^2)}{\frac{4.548 \times 300}{0.035} + \left[ 1 - 26.3 \left( \frac{373}{300} \right)^{\frac{10}{3}} \right]} = \frac{1.002 \times 20}{89,600} \\ &= 0.00051 \text{ atmospheres.}\end{aligned}$$

By the application, therefore, of a hydrostatic pressure of 20 atmospheres to the water at  $27^\circ \text{C}$ , the vapor pressure of the water is increased from 0.035 to approximately 0.03551 atmospheres.

If, on the other hand, a tension of 20 atmospheres is placed on the water, the vapor pressure of the water will be decreased by 0.00051 atmospheres, so that the relative humidity will become 98.5 per cent with respect to a free water surface at the same temperature. This humidity is close to that corresponding to the permanent wilting percentage.

Let us now consider several illustrations of the general usefulness and wide applicability of equation 239. Let us first develop the relation between the free energy  $\Delta f_v$  of a vapor and its vapor pressure  $p$  as previously given (eq. 159). Equation 239 may be changed to

$$v_L dP = v_V dp. \quad (249)$$

The specific volume of a liquid  $v_L$  is in general approximately constant with change of pressure, but the specific volume  $v_V$  of a vapor changes and may be assumed to follow approximately the ideal gas law

$$p v_V = RT.$$

Equation 249 becomes then

$$v_L dP = RT \frac{dp}{p}. \quad (250)$$

Consider the change in going from one equilibrium state  $A$  to another equilibrium state  $B$ . Integrating equation 250 between the limits of hydrostatic pressure  $P_A$  and  $P_B$  and the vapor pressure between the limits  $p_A$  and  $p_B$ , and recalling that  $v_L \Delta P$  (eq. 156) gives the change in free energy  $\Delta f$  of a liquid due to a change in hydrostatic pressure, we have

$$v_L(P_B - P_A) = v_L \Delta P = \Delta f = RT \ln \frac{p_B}{p_A}. \quad (251)$$

As the liquid and its vapor are assumed to be in equilibrium, their free energies must be the same (art. 22). Thus  $\Delta f = RT \ln \frac{p_B}{p_A}$  gives the free energy of both a liquid or a vapor in the state *B* with respect to that in the state *A*, expressed in terms of the vapor pressure. This agrees with article 39.

Going further with equation 251, we can derive Laplace's law of atmospheric pressure, which gives the variation in pressure *p* of a gas with

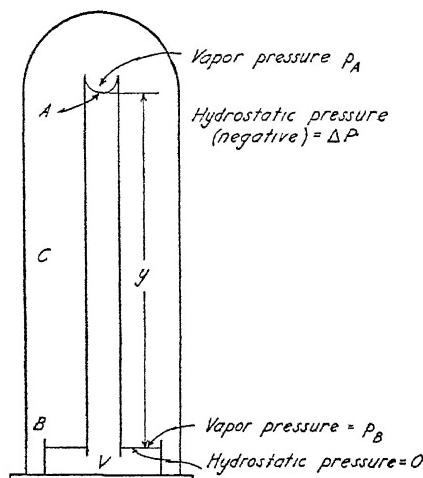


Fig. 20.—Equilibrium between vapor and liquid at different heights above a free water surface.

altitude *y*. The gas is to be situated in a uniform attractive force field of amount *g* dynes per gram. The law to be derived is

$$p_A = p_B e^{-\frac{gy}{RT}} \quad (252)$$

where *p<sub>B</sub>* is the vapor pressure at the height *y* = 0, *p<sub>A</sub>* that at the height *y*; and where *R* is the gas constant per gram. From equation 251 we have

$$\Delta f = f_A - f_B = v_L \Delta P = RT \ln \frac{p_A}{p_B}. \quad (253)$$

Consider figure 20. The chamber *C* encloses a long capillary tube of length *y* dipping into the free, pure water in the vessel *V*. Equilibrium has been established so that the vapor and the water are in equilibrium at all heights. In particular, the water under the meniscus *A* at the height *y* is in equilibrium with the vapor there. Also at the bottom *B*, the water

in the dish is in equilibrium with the vapor. Applying equation 253, we have for the hydrostatic pressure  $\Delta P$ , just below the meniscus at the height  $y$ ,

$$\Delta P = \frac{RT}{v_L} \ln \frac{p_A}{p_B}. \quad (254)$$

The hydrostatic pressure  $\Delta P$  just below  $A$ , with reference to that at  $B$  taken as zero, is equal to

$$\Delta P = -y \rho g \quad (255)$$

(that is, the weight of a column of liquid of unit cross section, height  $y$  and density  $\rho$ ). Combining equations 254 and 255, we have

$$\frac{RT}{v_L} \ln \frac{p_A}{p_B} = -y \rho g.$$

Since

$$\rho = \frac{1}{v_L},$$

then

$$\ln \frac{p_A}{p_B} = -\frac{gy}{RT}$$

or

$$p_A = p_B e^{-\frac{gy}{RT}},$$

which is recognized to be the same as equation 233 above and is therefore Laplace's law for the variation of vapor pressure with height in a uniform attractive field of force.

The general usefulness and applicability of equation 239 can be further illustrated by using it as the basis for deriving the relation between the osmotic pressure of a solution and its vapor pressure. As will be recalled (art. 24), the osmotic pressure is defined as the pressure that must be applied to a solution to place it in equilibrium with the pure solvent through a semipermeable membrane. From equation 239 we have

$$\frac{dP}{dp} = \frac{v_V}{v_L} \quad (256)$$

where now  $P$  will represent the osmotic pressure (that is, the hydrostatic pressure that must be applied to the solution to establish equilibrium with the pure solvent) and where  $p$  represents its associated vapor pressure. Equation 256 may be placed in the following form with the aid of the ideal gas law (art. 59):

$$dP = \frac{RT}{v_L} \frac{dp}{p} \quad (257)$$

where  $v_L$  is practically constant. Choosing the upper limit of integration of  $dP$  so that it is equal to the osmotic pressure  $\Delta P_O$  and consequently so that the vapor pressure of the solution has been raised from the normal value  $p$  to that of the pure solvent  $p_0$ , we have

$$\Delta P_O = \frac{RT}{v_L} \ln \frac{p_0}{p}. \quad (258)$$

As this equation shows, the osmotic pressure  $\Delta P_O$  is always positive, since  $p_0$  of the pure solvent is always greater than  $p$  of the solution.

The free energy of a solution due to the presence of dissolved material may be expressed immediately in terms of its vapor pressure as follows, after recalling equation 151:

$$\Delta f_O = -v_L \Delta P_O = -RT \ln \frac{p_0}{p}. \quad (259)$$

As this equation shows, the free energy  $\Delta f_O$  of a solution due to the presence of dissolved material is always negative.

#### 42. Dependence of the Hydrostatic Pressure in a Liquid on Its Surface Tension and Its Radius of Curvature

As will be recalled from equation 156, the change in the free energy  $\Delta f$  of a liquid caused by its being placed under a hydrostatic pressure  $\Delta P$  is given by

$$\Delta f = v \Delta P.$$

Equation 211 expresses the same  $\Delta f$  in terms of the radius of curvature  $r$  and surface tension  $\sigma$ . Combining both, we have

$$\Delta P = \frac{2\sigma}{r}. \quad (260)$$

If the vapor-water interface is concave to the vapor,  $r$  is negative, and equation 260 predicts a state of tension in the water. This corresponds to the conditions in unsaturated soils and capillary tubes. If, on the other hand, the vapor-water interface is convex to the vapor,  $r$  is positive, and 260 predicts a state of compression in the water. This corresponds to the conditions found in droplets of liquid.

#### 43. Effect of Surface Tension and Radius of Curvature of the Air-Water Interface on the Vapor Pressure of Soil Moisture

We wish to derive the expression

$$\ln \left( \frac{p}{p_0} \right) = \frac{v}{RT} \left[ \frac{2\sigma}{r} + (p_0 - p) \right] \quad (261)$$

for the vapor pressure  $p$  of the vapor over a curved vapor-water interface, expressed in terms of the surface tension of the water  $\sigma$ , the radius of curvature  $r$  of the vapor-water interface, and the vapor pressure over a free, flat water surface  $p_0$ . The terms  $R$ ,  $T$ , and  $r$  have their usual meanings; and the radius of curvature  $r$  of the curved vapor-water interface is taken as positive when the interface is convex, towards the vapor phase.

In our present case, since the surface is concave towards the vapor

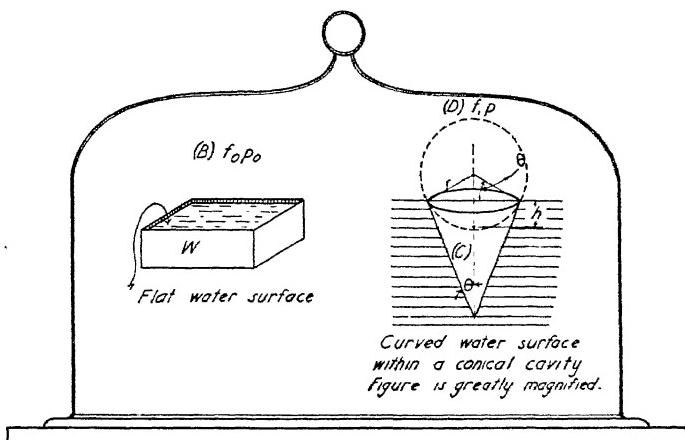


Fig. 21.—Flat water surface and a curved water surface in an enclosed chamber.

phase, we shall always substitute a negative value for  $r$ . In the succeeding development we shall also make use of the following terms:

$\theta = \frac{1}{2}$  the angle of the cone of water;

$h$  = height of the zone forming the curved water surface;

$A = 2\pi rh$  = area of zone forming the curved vapor-water interface;

$f, f_0$  = specific free energy of the vapor over the curved and free water surface, respectively.

To fix our ideas, consider figure 21, representing a wedge or cone of water whose vapor-water interface has a radius of curvature equal to  $r$ , and a vessel of free, pure water under its own vapor pressure, which we shall take to be the datum, or zero point, for free energy. The vapor pressure  $p_0$  over the free, flat water surface at the temperature  $T$  will be assumed to have reached equilibrium with the free water surface. Also the vapor pressure  $p$  over the curved water surface at the temperature  $T$  will be assumed to have reached equilibrium with the liquid water below the curved vapor-water interface. The two systems in the chamber will of course not be in equilibrium with each other. It follows (art. 22) that

the free energy  $f_0$  of the vapor at  $B$  equals the free energy of the water at  $W$ ; and the free energy  $f$  of the vapor at  $D$  equals that of the water at  $C$ . Hence the difference in the free energy between the vapor at  $D$  and  $B$  equals the difference in free energy between the liquids at  $C$  and  $W$ . In deriving equation 261 we shall therefore equate the difference or change in free energy between  $C$  and  $W$  to that between  $D$  and  $B$ .

The change in the free energy when  $dm$  grams of vapor are carried from  $B$  to  $D$  is (eq. 159)

$$(f - f_0) dm = RT \ln \left( \frac{p}{p_0} \right) dm. \quad (262)$$

Let us express  $dm$  in terms of the change in the radius of curvature  $dr$  of the interface. From any handbook of geometrical formulas giving the area of the zone of a sphere, we have for the area of the vapor-water interface

$$A = 2\pi rh. \quad (263)$$

Also from the geometry of the figure, we have

$$\sin \theta = \frac{r - h}{r};$$

that is,

$$h = r(1 - \sin \theta). \quad (264)$$

Inserting equation 264 into 263, we have

$$A = 2\pi r^2(1 - \sin \theta). \quad (265)$$

If  $dm$  grams of water are added to the curved surface of area  $A$ , a film of water of thickness  $dr$  is added to the curved surface. This corresponds to a volume

$$A dr = 2\pi r^2(1 - \sin \theta)dr;$$

and remembering that  $v$  is the specific volume, we have

$$dm = \frac{A dr}{v} = \frac{2\pi r^2(1 - \sin \theta)}{v} dr. \quad (266)$$

Inserting equation 266 into 262, we have, for the total amount of free energy required to transfer  $dm$  grams of vapor from  $B$  to  $D$ ,

$$(f - f_0)dm = \frac{2\pi r^2 RT(1 - \sin \theta)}{v} \ln \frac{p}{p_0} dr. \quad (267)$$

Now let us also calculate the free energy required to carry  $dm$  grams of liquid from  $W$  to  $C$ . This, of course, equals  $(f - f_0) dm$  (art. 22). To do this, let us recall the following fundamental relation between free energy and surface tension  $\sigma$ : the increase in the total free energy of a vapor-liquid interface when its surface area is increased by the amount  $dA$  is equal to  $\sigma dA$  (eq. 208). Also let us recall the following fact: the increase in the free energy of a gram of water when the hydrostatic pressure on the water is changed from  $P_0$  to  $P$  is given by  $v(P - P_0)$  (eq. 156). Thus in carrying water from  $W$  to  $C$ , two forms of free energy are involved. One is due to the increase of a surface area having a surface tension  $\sigma$ , and the other is due to the change of hydrostatic pressure. The first form of free energy is given by

$$\sigma dA = \sigma 4\pi r(1 - \sin \theta)dr \quad (268)$$

after differentiating  $A$  of equation 265 to get  $dA$ . The second form of free energy may be evaluated by carrying  $dm$  grams of water from  $W$ , where the hydrostatic pressure is  $p_0$  (produced by the vapor over  $W$ ), to  $C$ , where the hydrostatic pressure is  $p$  (produced by the vapor pressure  $p$  over  $C$ ). This gives

$$v(p - p_0)dm = v(p - p_0) \frac{2\pi r^2(1 - \sin \theta)}{v} dr, \quad (269)$$

making use of equations 156 and 266. The total change of free energy  $(f - f_0) dm$  in carrying  $dm$  grams of water from  $W$  to  $C$  is therefore the sum of equations 268 and 269, or

$$(f - f_0)dm = 4\pi r \sigma(1 - \sin \theta)dr + 2\pi r^2(p - p_0)(1 - \sin \theta)dr. \quad (270)$$

Equating 267 to 270 and rearranging, we have

$$\ln\left(\frac{p}{p_0}\right) = \frac{2\sigma v}{r RT} + \frac{(p - p_0)v}{RT}$$

or

$$\ln \frac{p}{p_0} = \frac{v}{RT} \left[ \frac{2\sigma}{r} + (p - p_0) \right]. \quad (271)$$

Since the difference in vapor pressures  $(p - p_0)$  is ordinarily so small with respect to  $\frac{2\sigma}{r}$ , it is ordinarily neglected; and we obtain the common form

$$\ln \frac{p}{p_0} = \left( \frac{v}{RT} \right) \frac{2\sigma}{r}. \quad (272)$$

Where  $r$  is negative, the logarithm must also be negative. We see, therefore, that the vapor pressure  $p$  over a concave surface is less than the vapor pressure  $p_0$  over a free water surface. Equation 272 can also immediately be placed in the form

$$p = p_0 e^{\frac{2v}{R\bar{T}} \frac{\sigma}{r}}.$$

Obviously, 272 also gives the vapor pressure outside of convex surfaces. In this case,  $r$  will be positive, because of our convention at the beginning as to the sign of  $r$ . In practice this might correspond to the determination of the vapor pressure in a closed vessel containing droplets of water of radius  $r$ . Equation 272 shows quantitatively how much greater the vapor pressure  $p$ , in equilibrium with the droplets, is than the vapor pressure  $p_0$  over a free water surface. The importance of taking the proper sign for the radius of curvature is thus emphasized.

#### 44. Comparison of Free Energy with Other Thermodynamic Functions Having Properties Similar to Free Energy

We shall begin by comparing the absolute free energy  $f$  with the thermodynamic function called "maximum work," which we shall symbolize by the letter  $a$ . Free energy is defined by

$$f = h - Ts = e - Ts + Pv. \quad (273)$$

Combining equations 48 and 70, we have

$$Tds = de + dw \quad (274)$$

where  $dw$  represents the total work done by the system, including any expansion against an external pressure  $P$ . Combining equations 274 and 273 after differentiation, we get

$$-df = s dT + dw - P dv - v dP.$$

If the temperature  $T$  is constant, this reduces to

$$-df = dw - P dv - v dP; \quad (275)$$

and if the pressure is also constant

$$-df = dw - P dv. \quad (276)$$

Let us, as in article 21, represent by  $dw_n$  all the work done by the system (this may include electrical and light energy) except any expansion

against an external pressure  $P$ . We then have  $dw_m = dw - P dr$ , and therefore equation 276 becomes

$$-df = dw_m. \quad (277)$$

That is, in any transformation of a system taking place at constant temperature and pressure, the decrease in the free energy of the system equals all the work done by the system such as that due to electrical- or light-energy changes; but it does not include work of expansion against the pressure  $P$ . When we are dealing with transformations of a substance from one phase to another at a constant temperature and pressure, the only mechanical work ordinarily done is that of expansion or contraction against the pressure  $P$ . Now  $dw_m$  does not include this work; hence, under these conditions,  $dw_m = 0$ , and therefore

$$-df = 0 \quad (278)$$

in any isothermal transformation of a substance at constant pressure from one phase to another. That is (art. 22), *all phases of a substance at the same temperature and pressure have the same free energy*. This fact is one chief justification for introducing the free-energy function in the study of soil moisture.

We shall find that the maximum-work function,  $a$ , is rather similar to  $f$  above. The main difference is that during any transformation of a substance from one phase to another at constant temperature and pressure, the change,  $da$ , is not zero, but equals the work of expansion or contraction against the external pressure  $P$ . Consequently, different phases of the same substance in equilibrium with each other do not have the same value for the maximum work  $a$ , as is true of the free energy  $f$ . In those cases where we wish to know the total work required to transform one phase of a substance into another, both in equilibrium with each other, we find that we should use the maximum-work function  $a$ .

The maximum work  $a$  is defined by

$$a = e - Ts. \quad (279)$$

Differentiating, we have

$$-da = -de + T ds + s dT,$$

and substituting for  $T ds$  from equation 274,

$$-da = s dT + dw. \quad (280)$$

If the temperature remains constant during the transformation,

$$-da = dw. \quad (281)$$

That is, during any transformation of a system at constant temperature, the decrease of the maximum work ( $-da$ ) equals all the work  $dw$  done by the system, including any expansion against an external pressure  $P$ . Now, as before,  $dw = dw_m + P dv$ ; and we have

$$-da = dw_m + P dv.$$

If we are considering isothermal transformations of a substance from one phase to another,  $dw_m$  is ordinarily zero, as before, since there are no light- or electrical-energy changes accompanying phase transitions. Consequently,

$$-da = P dv. \quad (282)$$

As will be noticed, our so-called system is, in this case, 1 gram of the substance in one phase being transformed into 1 gram of another phase—for example, 1 gram of ice being transformed isothermally into 1 gram of water. Equation 282 shows, therefore, that two phases existing in equilibrium with each other do not have the same value for the maximum work  $a$ ; their values differ by the work of expansion or contraction  $\int P dv$  against the external pressure  $P$ . The maximum-work function  $a$ , is therefore of great utility when we wish to calculate the total mechanical work required to transform isothermally a substance from one phase to another as, for example, in the transition of water from the liquid to the vapor state. The free-energy function  $f$ , on the other hand, has the advantage that when several phases are in equilibrium, they all have the same free energy; and the determination of the free energy in any one phase, such as the vapor phase, immediately gives the value of  $f$  for all the others.

Another advantage in using the free-energy function when dealing with such a substance as soil moisture is that free energy explicitly gives the amount of energy stored in the water because of hydrostatic pressure. This of course is not true for the maximum-work function. Since

$$dw_m = dw - Pdv,$$

we have, from equation 275,

$$-df = dw_m - vdP.$$

If the system performs no work other than that of expansion,  $dw_m$  will equal zero. Hence,

$$df = vdP;$$

and therefore an increase  $dP$  of the hydrostatic pressure in water, for example, will cause an increase in the free energy of the water equal to  $v dP$ , which is in agreement with equation 156.

A word of caution is perhaps appropriate here regarding the divergent terminology used by various authors in connection with such functions as free energy and maximum work.

Much confusion seems to have arisen since the thermodynamic functions  $f$  and  $a$  (or  $F$  and  $A$ , if one is dealing with 1 mol rather than 1 gram of the substance) were first proposed. According to Gibbs, what we now call the "free energy  $F$ " was originally called, by him, "thermodynamic potential" and symbolized by  $\zeta$ . Many European and some American physicists still use this terminology. Others, such as Haas, have used the symbol  $\phi$ . On the other hand, what we have here called the "maximum work  $A$ " was originally called by Helmholtz the "free energy" and by Gibbs in 1875 the "characteristic function  $\psi$ ." Most European and a few American physicists still use the symbol  $\psi$ ; but Haas, for example, still uses the letter  $F$ , calling it the "free energy" in agreement with the original work of Helmholtz. Since the original work by Helmholtz and Gibbs, some confusion has arisen among those working with the two functions: when supposedly dealing with what we now call the "maximum-work function," they have actually been dealing with what we now call the "free-energy function." This confusion probably arose because, in many calculations, the numerical values of  $\Delta F$  and  $\Delta A$  will be found to be identical or to differ very little. Since in practice, generally, the function

$$F = H - TS$$

is more important than the function

$$A = E - TS$$

the term "free energy" is now generally no longer associated with the latter function. Lewis and Randall use the terms "free energy  $F$ " and "maximum work  $A$ ," and we have followed this same terminology. They use the large letters  $F$  and  $A$ , because they are dealing with molal quantities; we use, however, the small letters  $f$  and  $a$ , since in studying soil moisture we always deal with specific quantities of the substance.

Still other functions similar to the free-energy function  $F$  have been used. Massieu in 1869 used, for deducing the thermodynamic properties of a fluid, functions that are actually the negative of our present functions  $F$  and  $A$  divided by  $T$ ; that is,  $\left(-\frac{F}{T}\right)$  and  $\left(-\frac{A}{T}\right)$ .

Planck, in his treatise on thermodynamics, does the same, finding that  $\left(-\frac{F}{T}\right)$  (which is what he calls the "characteristic function"  $\psi$ ) is a much more convenient function than  $F$  itself for dealing in a generalized way with systems containing a number of independent constituents, when one wishes to study the dependency of the equilibrium upon the temperature, pressure, and masses of the independent constituents of the system. In agreement with the pioneer work by Helmholtz, Planck uses the term "free energy," symbolized by  $F$ , to refer to the function we now call the "maximum work  $A$ ."

#### 45. Thomson, or Gibbs-Helmholtz, Equation

We can now derive one of the more fundamental equations of thermodynamics, which was discovered by Thomson in 1855. Later Gibbs, Helmholtz, van't Hoff, Nernst, and many others made numerous applications. Often, therefore, it is called the "Gibbs-Helmholtz equation." The maximum work  $a$  has been defined (eq. 279)

$$a = e - Ts.$$

From equations 280 and 93 we have

$$da = -s dT - dw = -sdT - Pdv - dw_m$$

so that if no work  $dw$  is done,

$$\left(\frac{\partial a}{\partial T}\right)_{v, w_m} = -s, \quad (283)$$

and therefore, by substituting this into the equation above, we obtain the Gibbs-Helmholtz equation,

$$a = e + T \left(\frac{\partial a}{\partial T}\right)_{v, w_m}. \quad (284)$$

Often we deal with changes  $\Delta a$  and  $\Delta e$  in a process rather than with  $a$  and  $e$  themselves. It is desirable, therefore, to restate 284 in terms of  $\Delta a$  and  $\Delta e$  rather than of  $a$  and  $e$ . If any reaction or transformation of a system takes place in such a manner that the maximum work  $a$  and the internal energy  $e$  change by the amount  $\Delta a$  and  $\Delta e$ , respectively, we have from  $a = e - Ts$ ,

$$\Delta a = \Delta e - T \Delta s \quad (285)$$

for a change taking place at a constant temperature. Now since equation

283 applies to the system both before and after the change in the system has taken place, we have

$$\left( \frac{\partial a_1}{\partial T} \right)_{v, w_m} = -s_1,$$

$$\left( \frac{\partial a_2}{\partial T} \right)_{v, w_m} = -s_2$$

where the subscripts 1 and 2 refer to the initial and final states, respectively, and therefore

$$\left[ \frac{\partial(a_2 - a_1)}{\partial T} \right]_{v, w_m} = -(s_2 - s_1)$$

or

$$\left( \frac{\partial \Delta a}{\partial T} \right)_{v, w_m} = -\Delta s.$$

Substituting this into equation 285, we have

$$\Delta a = \Delta e + T \left( \frac{\partial \Delta a}{\partial T} \right)_{v, w_m}, \quad (286)$$

showing the relation between changes in the maximum work  $\Delta a$  and the internal energy  $\Delta e$  of a system during an isothermal change or transformation.

If, instead of dealing with the maximum work  $a$ , we deal with the free energy  $f$ , we obtain a set of equations similar to those above. Briefly, we have (eq. 92)

$$f = h - Ts.$$

From equation 97 we have the differential of the above

$$df = -s dT + v dP - dw_m$$

so that

$$\left( \frac{\partial f}{\partial T} \right)_{P, w_m} = -s. \quad (287)$$

Substituting this into equation 92, we have

$$f = h + T \left( \frac{\partial f}{\partial T} \right)_{P, w_m}, \quad (288)$$

which is similar in form to equation 284. Likewise, if we are dealing with changes  $\Delta f$  and  $\Delta h$  of  $f$  and  $h$ , we have for an isothermal change

$$\Delta f = \Delta h - T \Delta s. \quad (289)$$

And, as previously, since equation 287 applies to the system both before and after the change has taken place, we have

$$\left( \frac{\partial f_1}{\partial T} \right)_{P, w_m} = -s_1,$$

$$\left( \frac{\partial f_2}{\partial T} \right)_{P, w_m} = -s_2;$$

consequently

$$\left[ \frac{\partial(f_2 - f_1)}{\partial T} \right]_{P, w_m} = -(s_2 - s_1)$$

or

$$\left( \frac{\partial \Delta f}{\partial T} \right)_{P, w_m} = -\Delta s.$$

Substituting this into equation 289, we have

$$\Delta f = \Delta h + T \left( \frac{\partial \Delta f}{\partial T} \right)_{P, w_m},$$

giving the relation between changes of  $f$  and  $h$  in a system undergoing an isothermal change. Here, of course, we are dealing with changes of the heat content  $\Delta h$  rather than of the internal energy  $\Delta e$  as in equation 286; here the partial differentiation is with the pressure rather than the volume constant, while  $w_m$  is held constant for both differentiations.

#### 46. Relation between Surface Tension, Total Surface Energy per Unit Area, and Temperature

As a result of molecular attraction, the molecules of the surface of a liquid substance are acted upon by a force at right angles to the surface and directed toward the interior of the liquid. This force of attraction is produced by the molecules of the liquid adjacent to the surface and is also the source of the tangential tension over the vapor-liquid interface that we call "surface tension." When the area of such an interface is increased, additional molecules must be pulled from the interior of the liquid into the interface against the force of attraction of the molecules making up the body of the liquid. Work, consequently, must be expended to increase the area of the interface; and the behavior of the interface therefore somewhat resembles a stretched elastic membrane.

The velocities of the molecules are distributed among the different molecules of the liquid according to the Maxwell distribution law (art.

54). Thus the kinetic energies of the different molecules will vary widely. Some molecules will have sufficient kinetic energy to carry them beyond the range of the attractive force of the liquid and into the vapor phase, whereas others will be able to get only part way into the vapor phase. For this reason, there exists a transition layer between liquid and vapor, in which the density grades from that of the liquid to that of the vapor. The formation of this layer of intermediate densities furnishes the basis for explaining the fact that a cooling generally occurs when the area of the interface is increased. Clearly, an adiabatic expansion of the liquid against the force of molecular attraction takes place in the formation of

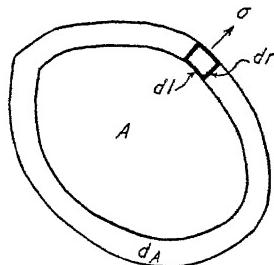


Fig. 22.—An expanding surface.

the transition layer, since part of the liquid moves into the transition layer where the density is lower. Thus, as with the adiabatic expansion of a gas when no external work is done, cooling occurs according to the Joule-Thomson effect, in addition to the slight amount of work done in the expansion against atmospheric pressure. To form a fresh surface isothermally, therefore, work must be done against surface tension, and heat must be added to prevent cooling.

Assume that an area  $A$  (fig. 22) is increased to  $A + dA$ . The quantity  $(\sigma dA)$  of article 32 does not represent the total energy expended when a fresh interface of area  $dA$  is formed. When such an increase in area at the interface takes place adiabatically, it is shown below that a quantity of heat  $\left(-T \frac{d\sigma}{dT}\right)$  per unit area is absorbed from the interior, which is therefore cooled.

Let us now derive the relation between this heat, the surface tension  $\sigma$ , and the total surface energy  $e_A$  per unit area, the energy  $e_A$  being localized in the surface layer of thickness  $\tau$  taken up in article 32. The work done by the surroundings on the liquid at constant temperature because of surface tension is, according to equations 101 and 208,

$$-\Delta w_s = \int (\sigma dl) dr. \quad (290)$$

The negative sign indicates that work is actually done on the liquid by the surroundings in creating the element of surface ( $dldr$ ). Since the temperature is constant (eq. 281), we may write

$$\Delta a = \int (\sigma dl) dr = \sigma \Delta A . \quad (291)$$

There is no appreciable expansion against atmospheric pressure in the formation of a new surface. It follows, therefore, that  $\Delta a = \Delta f$  in this case since the term  $Pdv$  of equation 276 is approximately zero. That is,

$$\Delta a = \Delta f = \sigma \Delta A .$$

The term  $\Delta a$  will, however, be most convenient for the immediate purpose. (If we were to follow strictly the conventions of article 10 as to symbols, we should use capital letters here instead of  $f$ ,  $w$ ,  $a$ , and  $e$ . The use of capital letters here might lead to confusion because other meanings have already been assigned to such letters as  $A$ . If it be remembered that the symbols  $f$ ,  $w$ ,  $a$ , and  $e$  in this paragraph refer not to 1 gram of water but rather to unit area of the surface, the reasoning and conclusions will in no way be altered.) The increase in total surface energy is

$$\Delta e = e_A \Delta A , \quad (292)$$

where  $e_A$  is the total surface energy per unit area. As lately shown (art. 45), the Gibbs-Helmholtz equation (286) is

$$\Delta a = \Delta e + T \left( \frac{\partial \Delta a}{\partial T} \right)_{v, w_m} . \quad (293)$$

Inserting equations 291 and 292 into 293, we have

$$\sigma \Delta A = e_A \Delta A + T \left[ \frac{\partial (\sigma \Delta A)}{\partial T} \right]_{v, w_m}$$

or

$$\sigma = e_A + T \left( \frac{\partial \sigma}{\partial T} \right)_{v, w_m} \quad (294)$$

or

$$e_A = \sigma - T \left( \frac{\partial \sigma}{\partial T} \right)_{v, w_m} . \quad (295)$$

Equation 295 relates the surface tension  $\sigma$  to the total surface energy per unit area  $e_A$  and the temperature of the surface  $T$ .

In using equation 295 it is necessary to evaluate  $\left( \frac{\partial \sigma}{\partial T} \right)$ . This has been

done by several investigators. The expressions obtained are largely empirical. For water, probably the most commonly accepted relation that may be used for evaluating the differential coefficient is the empirical relation given by equation 434. There is also the Ramsay-Shields equation:

$$\sigma(Mv)^{\frac{2}{3}} = k(T_c - 6 - T) \quad (296)$$

where  $M$  is the molecular weight,  $T_c$  the critical temperature of the liquid,  $T$  the temperature of the liquid surface,  $v$  the specific volume, and  $k$  a constant for the given liquid. The value of  $k$  is approximately the same for all

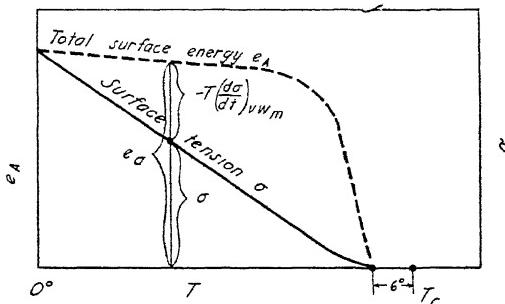


Fig. 23.—Relation between surface tension, surface energy, and temperature of a surface.

liquids that exist as simple undissociated molecules, such as benzene, carbon tetrachloride, and carbon disulfide. For these liquids,  $k$  is equal to approximately 2.12 when surface energy is expressed as ergs per square centimeter. For liquids whose molecules are associated in the liquid state into double or more complex molecules, such as water, methyl and ethyl alcohols, and acetic acid,  $k$  has a smaller value than 2.12 and varies with the liquid.

The general form of the linear decrease in the surface tension  $\sigma$  with rise in temperature  $T$  (eq. 434 and 296) is shown in figure 23. As the graph shows,  $\sigma$  approaches zero at a temperature approximately 6 degrees below the critical temperature. The critical temperature  $T_c$  for water, at which the liquid and vapor become identical, is 647° A.

According to equation 295, since  $\left(\frac{\partial\sigma}{\partial T}\right)$  is negative, the curve representing  $e_A$  always falls above the curve representing  $\sigma$ . Also, since  $\left(\frac{\partial\sigma}{\partial T}\right)$  is nearly constant,  $\left[-T\left(\frac{\partial\sigma}{\partial T}\right)\right]$  is positive and of such a magnitude that it represents approximately the difference between  $\sigma$  at 0° A and  $\sigma$  at the

temperature in question. Thus when this value is added to  $\sigma$  to get  $e_A$  (eq. 295 and fig. 23), we find  $e_A$  remaining nearly constant with change of temperature until the critical temperature is neared, at which  $e_A$  becomes zero, since  $\left(\frac{\partial\sigma}{\partial T}\right)$  and  $\sigma$  become zero there.

By comparing equation 295 and the statement of the First Law of thermodynamics (eq. 47), we note that  $\left[-T\left(\frac{\partial\sigma}{\partial T}\right)\right]$  represents the heat  $\Delta q$  required for isothermal formation of unit surface area, since  $e_A$  corresponds to  $\Delta e$  and since  $(-\sigma)$  corresponds to  $\Delta w$ . As will be recalled,  $\Delta w$  is the work done by the liquid surface on its surroundings during the isothermal formation of the liquid surface. Consequently, if the extension of the liquid surface were carried out adiabatically, a quantity of heat  $\left[-T\left(\frac{\partial\sigma}{\partial T}\right)\right]$  would be absorbed from the interior of the liquid, whose temperature would consequently drop. When the new surface is created isothermally, this quantity of heat is added by the surroundings to the surface layer to compensate for the cooling effect; it may be called the latent heat of surface formation.

## KINETIC THEORY OF SOIL MOISTURE

### 47. Dependence of the Properties of Soil Moisture on the Velocities and Energies of the Individual Molecules

In dealing with a substance such as soil moisture, we may generally assume that any one molecule has the same properties and is in the same condition as any one of those adjacent to it. We know that any single water molecule in soil moisture has the same structure as any other. Presumably, too, within any sufficiently small region of soil moisture, all the molecules are acted upon by the same forces, while the temperature and the hydrostatic pressure in the water are the same throughout.

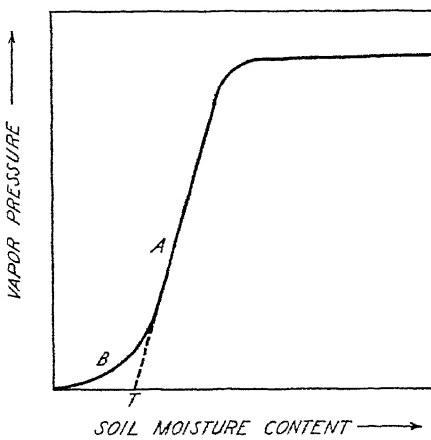


Fig. 24.—Dependence of the vapor pressure of soil moisture on the soil moisture content.

Likewise, in considering the vapor phase at equilibrium, we assume the vapor pressure and the temperature to be the same throughout.

Certain physical phenomena lead one, however, to suspect that although the elementary water molecules may be chemically alike, each one may carry properties or characteristics widely different from those of its neighbors. A single molecule in a large group possesses characteristics (such as velocity of translation, momentum, kinetic energy, and the energy of vibration of the atoms composing it, as well as their potential energy) widely different from the properties of the adjacent molecule.

Let us consider how these facts affect the explanation for the shape of the curve showing the relation between the soil moisture content and the vapor pressure of the soil moisture at low moisture contents. Experimentally (fig. 24) we know that as the soil moisture content is decreased, the vapor pressure decreases (part A of the curve). The vapor pressure is

never zero, no matter how small the moisture content, since the curve bends over along the part *B*. As has been shown by Kelley, Jenny, and Brown (95), the *B* part of the curve is irregular because of water of crystallization.

Actually, one would expect the vapor pressure of the soil moisture to become zero for some finite soil moisture content if all the water molecules had the same velocity and kinetic energy. Consider figure 25. As the soil moisture content decreases (in other words, as the interface *I* moves in towards the soil particle), the water molecules at the interface are more and more influenced by the adsorptive force of the soil particle. At the same time, consequently, more and more work is required to free a water

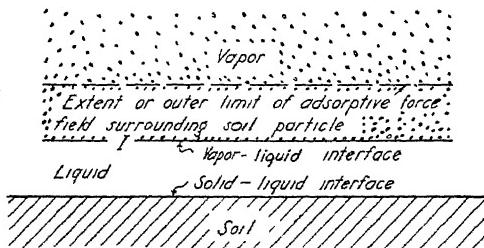


Fig. 25.—Thin layer of soil moisture in the adsorptive force field.

molecule completely from the liquid and to carry it into the free vapor state. A water molecule in the interface *I* will always be able to escape into the free-vapor state as long as the component of its velocity normal to the soil surface gives it a kinetic energy greater than the work required to carry the molecule out of the interface into the free vapor state as shown in article 55. As the soil moisture content decreases (and, therefore, as the work required for the removal of a water molecule into the vapor phase increases), we shall reach a point corresponding to a finite soil moisture content where the vertical component of the kinetic energy of the molecule can no longer carry the molecule out from the interface *I* into the free vapor state. At this moisture content and at all those less than this, the molecule will remain bound to the liquid layer. Evidently, then, if all the water molecules of a body of soil moisture had the same velocity and, therefore, the same kinetic energy, we should expect to find the vapor pressure of a moist soil zero over the lowermost range of soil moisture contents. Here there is a close analogy between the vertical component of the velocity that a rocket must have in order to escape permanently from the surface of the earth, and the velocity that a molecule in the soil moisture must have in order to escape permanently into the

vapor phase. If the rocket has not enough kinetic energy, it will not escape permanently.

If, on the other hand, the velocities of the different molecules varied widely, we should not expect the vapor pressure of the soil moisture to become zero abruptly at some finite soil moisture content. As the soil moisture content is decreased, the work required to remove a molecule from the soil moisture always increases, and consequently the minimum velocity that a molecule may have and still escape is also increased. As the soil moisture content is decreased, accordingly, more and more molecules find themselves bound because of insufficient velocity or kinetic energy. The fastest molecules always escape, but the number that can escape is diminished gradually as the soil moisture content is decreased. We should, therefore, expect to observe a gradual rather than an abrupt decrease of the vapor pressure with a decrease of soil moisture content if the velocities of the water molecules vary widely. Experimentally (2, 39, 42, 46, 153, 154) we always find a gradual decrease, never an abrupt decrease, of the vapor pressure with a decrease of soil moisture content.

The effect of increasing the temperature is always to increase the momentums and velocities of all the molecules and consequently their ability to escape. We therefore always find an increase of the vapor pressure of soil moisture with a rise of temperature.

Since, in the subject of soil moisture, the solution of many problems will, in the future, depend upon an accurate knowledge of how the individual molecules of a substance are distributed among the different possible velocity and kinetic-energy states, we shall now take up the basic theory for solving such problems. An analogy to the situation above, in which we considered the distribution of molecules among different velocity or energy states, is represented by the distribution of the population of a country according to yearly income. Some in the population have a very small income; some very large; but the majority are clustered about the "most probable income." The incomes (or velocities by analogy) vary from one individual to the next, and a distribution curve would show how the different individuals are distributed among the different intervals or brackets of income. The distribution of incomes among the different individuals is then bound by the condition that if one multiplies the number of individuals belonging to each interval, or "bracket," of income by the value of the income for that interval and then takes the sum of these products over all intervals, the result will give the total annual income of the population. The distribution is bound also by the condition that the total number of individuals of the population shall remain the same during the determination. In fact, the mathematical treatment is exactly like the one to be followed for molecules.

#### 48. Meanings of Terms to Be Used in the Statistical Analysis of Molecular Velocities and Energies

Let us consider the meaning associated with several terms. We must distinguish between the macroscopic and microscopic states of a substance. A "macroscopic" state is one determined by quantities such as temperature and pressure, which can be measured by ordinary methods. For example, the macroscopic state of an ideal gas at equilibrium is entirely determined by only two variables, such as pressure and temperature. The "microscopic" state, on the other hand, requires, for its specification, that the position and motion of all parts of the substance be determined in detail. For example, the microscopic state of an ideal gas at equilibrium is not determined merely by two variables such as pressure and temperature; for its specification one must know the positions and velocities of all the molecules composing the gas. Relatively speaking, a knowledge of the macroscopic state of a substance at equilibrium is a rather superficial bird's-eye sort of information, whereas knowledge of the microscopic state of a substance is a complete and detailed description of the parts and their interrelations.

Evidently, then, for the same macroscopic state of a substance, there may be numerous microscopic states. Let us consider a volume of water vapor sufficient to hold 1 mol under standard conditions of temperature and pressure. Its macroscopic equilibrium state is determined by any two of such quantities as  $p$ ,  $v$ ,  $T$ ,  $f$ , or  $s$ . Its momentary microscopic state, on the other hand, requires for its specification both the position and motion of each of the molecules in the vessel; and there are  $6.06 \times 10^{23}$  of them! The molecules all have different positions in the vessel, and their velocities vary widely. Suppose now we interchange two of them with respect to their instantaneous location. Obviously, the  $T$ ,  $p$ ,  $v$ ,  $f$ , and so forth of the gas will not be affected; that is, the macroscopic state of the water vapor will remain the same. Its microscopic state, on the other hand, is not the same; instead, we have actually created a new microscopic state. The same holds true if we interchange the velocities associated with two different molecules. The macroscopic state remains the same, but the microscopic state is new. Such quantities as internal energy, temperature, pressure, and consequently the macroscopic state of the substance all remain the same in all interchanges of position and motion of the molecules. Meanwhile, the microscopic state does not remain the same; each interchange of the velocity or position of two molecules creates a new one. Since the volume of vapor we have been considering contains  $6.06 \times 10^{23}$  molecules, evidently we could create innumerable different microscopic states, corresponding to the one macroscopic state, by making all possible interchanges of the velocities and positions among the molecules.

Often in statistical mechanics, one encounters the term "complexion." This is completely synonymous with "microscopic state." Each new microscopic state corresponds to a different complexion; and for each macroscopic state there are many complexions. Since the two terms have the same meaning, we will use "complexion" in place of microscopic state to avoid an annoying similarity in spelling and pronunciation.

At equilibrium the molecules of water vapor are in continuous motion and are continually colliding, changing their positions and velocities. The complexion of the vapor is therefore continually changing with lapse of time, although the macroscopic state of the vapor and the quantities that determine it remain the same. The quantities determining the macroscopic state are averages over all the molecules in the given volume for a finite interval of time; they remain constant within the limits of sensitivity of our ordinary instruments of observation.

Why, then, one might ask, is the complexion of a substance at equilibrium always changing even though the macroscopic state remains apparently the same? The answer must be that all or most of the different complexions in which the substance exists from time to time, correspond to the same or nearly the same macroscopic quantities such as  $p$ ,  $v$ ,  $T$ , that define the equilibrium macroscopic state. Consequently, there must be extremely few and short-lived complexions of the substance whose macroscopic quantities differ widely from those of the average, normal, or most probable macroscopic state. Any that do arise disappear almost immediately. Thus the number of complexions associated with any macroscopic state appreciably different from the equilibrium macroscopic state must be negligible when compared with the entire number of possible complexions in which the substance may exist over a long period.

If the substance is not in equilibrium throughout, it will be in some nonequilibrium macroscopic state (depending upon the temperature and pressure throughout), with which are also associated several different complexions. But in this case the number of different possible complexions is relatively small as compared with the total number of different complexions by which the equilibrium macroscopic state can be realized. The equilibrium state of a substance corresponding to a given temperature and pressure is therefore that macroscopic state (of all those conceivable at the particular temperature and pressure) which has associated with it the greatest number of different complexions and can therefore be realized in the most ways. A substance not in equilibrium throughout is continually changing from a macroscopic state having few complexions to one having many. The equilibrium macroscopic state is, therefore, the one associated with a maximum number of complexions; that is, the equilibrium state is the most probable, since it can be realized in the most ways.

Our problem now, therefore, will be to obtain a quantitative expression for the probability of occurrence (that is, the total number of microscopic states) of a particular macroscopic state of a substance and to find out under what conditions the probability is a maximum. These conditions will then serve to describe completely the equilibrium state of the substance, since they define or determine the most probable state. Our problem for the present, accordingly, is mainly one of statistics.

#### 49. Molecular Statistics

Consider, for example, an assembly of molecules having a mass of 1 gram. Suppose we wish to study and determine the speeds of each individual molecule.

	2 7 11	14 5 6 9		3 8 12	10	
Speed of molecule	$du$	$2du$	$3du$	$4du$	$5du$	$6du$
Interval number ( $n$ )	1	2	3	4	5	6
Number of molecules $N_n$ lying in interval $n$ (Total number of molecules is $N = 12$ )	$N_1 = 3$	$N_2 = 0$	$N_3 = 5$	$N_4 = 0$	$N_5 = 3$	$N_6 = 1$

Fig. 26.—Distribution of molecules in velocity space.

vidual molecule when the entire system is in a state of equilibrium. To do this let us divide the total range of possible speeds that a molecule might possess into a series of equal intervals of amount  $du$ . This gives us a plurality or series of different speed states in which a given molecule might exist and enables us to classify the different molecules on the basis of their speed.

We then ask how, under a given set of conditions, the different molecules are distributed among the different speed states. Take, for example, the hypothetical case of 12 molecules and divide the total range of possible speeds that a molecule might possess into six equal intervals of amount  $du$  (fig. 26). Any molecule happening to be in interval 3 has 3  $du$  units of speed; in interval 5, 5  $du$  units of speed, and so on. The figure shows one particular complexion of a definite macroscopic state in which 3 molecules are in the first and fifth interval, 5 in the third, and 1 in the sixth. By interchanging, for example, molecules 10 and 2, which are in different compartments, we obtain another complexion; but the macroscopic state remains unchanged. If, on the other hand, we interchange

two molecules in the same speed state, we change neither the macroscopic state nor the number of complexions. Different complexions are formed, therefore, only by interchanging molecules that are in different and distinct states or intervals. Evidently we can obtain many other complexions, all having the same macroscopic state, by interchanging different molecules between different states or intervals. Only by changing the total number of molecules in each compartment or interval can we change the macroscopic state.

As stated in the previous section, the equilibrium state of a substance, at a given temperature and pressure, is the most probable macroscopic state; it is the one, at the given temperature and pressure, out of which can be formed the greatest number of different possible complexions.

Let us define the "thermodynamic probability"  $W$  of a given macroscopic state as the number of different complexions that will produce that state. It cannot be too strongly emphasized that we use synonymously the three terms "thermodynamic probability"  $W$ , "number of microscopic states"  $W$ , and "number of complexions"  $W$ . The term "probability" originated in pure mathematics; the terms "complexion" and "microscopic state" in the field of physics. Figure 26 shows one complexion of a particular macroscopic state. Let us, for example, determine the total number of possible complexions which will produce the same macroscopic state shown in the figure—that is, in which any 3 molecules are in the first interval, 0 in the second, 5 in the third, 0 in the fourth, 3 in the fifth, and 1 in the sixth. The total number of possible complexions is given by the well-known permutation formula for a totality of  $N$  objects, which are divided into groups of  $N_1, N_2, N_3, \dots$ . The thermodynamic probability  $W$  is equal to the number of complexions corresponding to the one macroscopic state in which  $N_1$  molecules have a speed  $du$ ,  $N_2$  a speed  $2du$ , and so on, up to the last velocity interval  $i$  in which  $N_i$  molecules each has a speed  $idu$ . Thus

$$W = \frac{N!}{N_1! N_2! \dots N_n! \dots N_i!}. \quad (297)$$

This formula becomes self-evident if one considers that if all the  $N$  molecules possessed different speeds (that is, fell in different speed intervals so that there would be  $N$  different speed intervals), the number of different possible complexions would equal the number of permutations of the  $N$  different molecules, each permutation containing all the molecules; that is,  $N! = (N)(N - 1)(N - 2) \dots (3)(2)(1)$  complexions. Now when  $N_1$  of the  $N$  molecules are identical (that is,  $N_1$  molecules fall in the same speed interval), let the number of different complexions or

permutations be  $Y$ . If, however, the  $N_1$  identical molecules were each given a different speed, factorial  $N_1$  ( $N_1!$ ) different complexions or permutations could be formed from each of the  $Y$  complexions. Therefore

$$Y N_1! = N!$$

because of the well-known theorem that if one situation can happen in  $a$  ways and another in  $b$  ways, then the compound situation composed of both of them can happen in  $ab$  different ways. In like manner it is shown that when the molecules are divided into several groups containing  $N_1$ ,  $N_2$ ,  $N_3$ , . . . , identical molecules (the speed of each molecule in a given group being the same), the number of permutations or complexions corresponding to the given macroscopic state equals the expression for  $W$  given by equation 297.

To bring out more concretely the meaning of equation 297, let us apply it to the calculation of the total number of possible complexions corresponding to the macroscopic state shown. Recalling from elementary algebra that  $0! = 1$ , we have

$$W = \frac{12!}{3!0!5!0!3!1!} = 110,880 \text{ complexions.}$$

That is, the given macroscopic state can be realized in 110,880 different ways.

Let us digress for a moment to generalize this treatment so that it may be applied to an actual substance such as water vapor. Above, for purposes of illustration, we have considered essentially only a one-dimensional array of velocity states in which the representative point of any one molecule is given by but one value of velocity. We have thus, in the above, confined our attention to only one of the three components of velocity of a molecule. Actually a molecule has, in general, three components of translational velocity,  $u_x$ ,  $u_y$ , and  $u_z$ , along three coördinate axes, associated with the three translational degrees of freedom. Besides the translational degrees of freedom, or movements, a polyatomic molecule may have rotational and internal movements or degrees of freedom that arise because of the relative motions of the atoms with respect to each other within the molecule. Each of these degrees of freedom will have energy associated with it.

In general, therefore, when we consider a substance such as water vapor, whose molecules are all alike, we shall assume that each molecule has  $d$  degrees of freedom, not merely 1, as in the elementary example used. The state of any one molecule is then defined at any moment by the  $d$  generalized coördinates of position of the molecule in space as well as the  $d$  generalized coördinates of velocity (associated with the  $d$  coördi-

nates of position) necessary to describe completely the whole movement of the molecule (both translational and interatomic). Thus  $2d$  independent variables are required to specify the state of the molecule. This means that the state of a molecule is fixed only when both its position and movements are fixed. Let us use these  $2d$  variables as coördinates in a  $2d$  dimensional space that we shall call, for short, the "phase space" or "state space." The state of each molecule is then specified by a point (henceforth called the "representative point" of the molecule) in this space. There will be as many representative points in the space as molecules in the substance. Since the molecules are always moving, the representative points in the phase space will also be in continuous motion describing what may be called "phase paths." If the vapor, for example, is composed of  $N$  molecules, the instantaneous complexion of the substance is specified at any moment by the location of all the  $N$  representative points in the phase space.

Let us divide this  $2d$  dimensional phase space into small compartments, boxes, or cells, all of equal size  $g$ . Then the instantaneous complexion of the substance is completely defined when we know in which cell each individual representative point lies, in the same manner as we previously knew the instantaneous state of our hypothetical vapor when we knew in which cell or interval of our one-dimensional velocity space each individual representative point fell.

Our definition of the term "complexion" also remains the same. When we interchange molecules between two different cells in the phase space, we keep the macroscopic state of the system the same but create a new complexion.

At first it may seem strange to speak of cells and compartments that have more than three dimensions. Although it seems impossible to visualize more than three, we are not handicapped by any such limitations in mathematics, where we can deal with a space of as many dimensions as we please. Since these multidimensional spaces have properties analogous to the three-dimensional spaces of ordinary experience, we often apply many of the terms associated with the latter to the former.

After this digression, we are now able to treat statistically the case of an actual substance and the behavior of its molecules.

We recall that since we are interested in the state of thermodynamic equilibrium, we are interested in that macroscopic state whose thermodynamic probability  $W$  is a maximum; that is, we want that distribution  $N_1, N_2, \dots, N_s$  of the molecules among the different compartments in phase space which will make  $W$  a maximum. Before we can determine this mathematically according to equation 297, we must simplify the expression for the statistical probability  $W$  to a form that may be handled more

easily. To do this, we must use an easily derivable mathematical formula of approximation for  $N!$  given by equation 304. We shall derive this now. Making use of the identities,

$$\ln N! = \ln 1 + \ln 2 + \ln 3 + \dots + \ln N \quad (298)$$

and

$$\ln N^N = \ln N + \ln N + \ln N + \dots + \ln N. \quad (299)$$

Consequently, since the difference between the logarithms of two numbers is always equal to the logarithm of their quotient—that is

$$(\log a - \log b) = \log \frac{a}{b} \text{—we have (eq. 298 and 299)}$$

$$\ln \frac{N!}{N^N} = \ln \frac{1}{N} + \ln \frac{2}{N} + \dots + \ln \frac{N}{N}. \quad (300)$$

Equation 300 may be graphically represented by an area as in figure 27.

If we multiply equation 300 by  $\frac{1}{N}$ , a little consideration of the right side of the equation will show that  $\frac{1}{N} \log \frac{N!}{N^N}$  is equal to the area between the

curve and the vertical axis, between the limits  $\frac{1}{N}$  and  $\frac{N}{N}$ . Strictly speaking, the shaded areas should be included; but if  $N$  is large, as always when we are dealing with vapors, these may be neglected. To find this area and consequently the value of  $\log \frac{N!}{N^N}$  let us set

$$dx = \frac{1}{N}.$$

Equation 300 then becomes, after multiplying both sides by  $\frac{1}{N} = dx$ ,

$$\frac{1}{N} \ln \frac{N!}{N^N} = \ln(dx)dx + \ln(2dx)dx + \dots + \ln(Ndx)dx. \quad (301)$$

From this equation and from the very definition of an integral, it follows that

$$\frac{1}{N} \ln \frac{N!}{N^N} = \int_0^1 \ln x dx, \quad (302)$$

where it is evident, as in figure 27, that the limits of integration of  $x$  are 0 and +1. Integrating, we have

$$\int_0^1 \ln x \, dx = \left[ x \ln x - x \right]_0^1 = -1.$$

Consequently

$$\frac{1}{N} \ln \frac{N!}{N^N} = -1$$

or

$$\ln \frac{N!}{N^N} = -N. \quad (303)$$

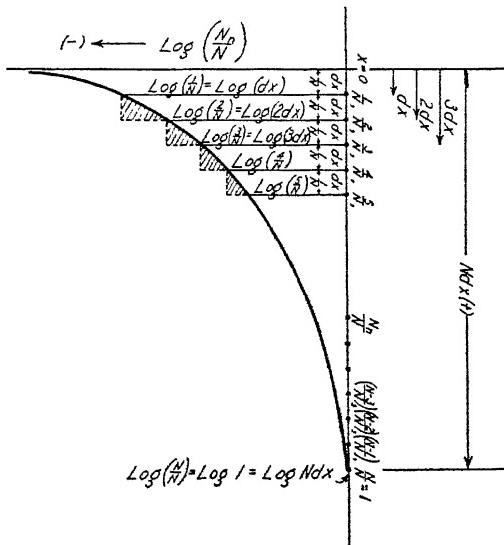


Fig. 27.— $\log \left( \frac{N!}{N^N} \right)$  plotted as a function of  $\left( \frac{N!}{N^N} \right)$ .

But according to the definition of the natural logarithm whose base is  $e$ , we have  $\ln e^N = N$ . Equation 303 then becomes

$$\ln \frac{N!}{N^N} = -\ln e^N.$$

Rearranging, we have

$$\ln (N!) - \ln N^N = -\ln e^N$$

or

$$\ln (N!) = \ln \frac{N^N}{e^N} = \ln \left( \frac{N}{e} \right)^N$$

so that

$$N! = \left(\frac{N}{e}\right)^N \quad (304)$$

enabling us to replace factorial  $N$  by the  $N$ th power of  $\left(\frac{N}{e}\right)$ .

Making use of equation 304, we may now simplify the expression for the thermodynamic probability  $W$ —that is, the number of different complexions corresponding to a given macroscopic state (eq. 297). We have

$$\begin{aligned} W &= \frac{\left(\frac{N}{e}\right)^N}{\left(\frac{N_1}{e}\right)^{N_1} \left(\frac{N_2}{e}\right)^{N_2} \left(\frac{N_3}{e}\right)^{N_3} \dots \left(\frac{N_n}{e}\right)^{N_n} \dots \left(\frac{N_i}{e}\right)^{N_i}} \\ &= \frac{N^N}{N_1^{N_1} N_2^{N_2} N_3^{N_3} \dots N_n^{N_n} \dots N_i^{N_i}} \end{aligned}$$

since  $N = (N_1 + N_2 + \dots + N_i)$ . Consequently

$$\begin{aligned} \ln W &= \ln N^N - \ln (N_1^{N_1} N_2^{N_2} N_3^{N_3} \dots N_n^{N_n} \dots N_i^{N_i}) \\ &= N \ln N - N_1 \ln N_1 - N_2 \ln N_2 - N_3 \ln N_3 - \dots - N_n \ln N_n - \dots \\ &\quad - N_i \ln N_i \\ &= N \ln N - \sum_{n=1}^{n=i} N_n \ln N_n. \end{aligned} \quad (305)$$

Let us now put

$$w_1 = \frac{N_1}{N}, \quad w_2 = \frac{N_2}{N}, \quad \dots, \quad w_n = \frac{N_n}{N}, \quad \dots, \quad w_i = \frac{N_i}{N} \quad (306)$$

and consequently

$$w_1 + w_2 + w_3 + \dots + w_n + \dots + w_i = 1 \quad (307)$$

since  $N = (N_1 + N_2 + \dots + N_i)$ . That is,  $w_n$  represents the fraction of the total number of molecules  $N$  whose representative points fall in the  $n$ th compartment or cell of phase space. All the molecules whose representative points fall in the same cell of phase space are in the same state in every respect, within the limits imposed by the finite but small dimensions of an individual cell. We will also call  $w_n$  the mathematical probability that a given molecule is in the state corresponding to the  $n$ th

compartment or cell in phase space. Applying equation 306 to 305, we have

$$\begin{aligned}\ln W &= N \ln N - N w_1 \ln N w_1 - N w_2 \ln N w_2 - \dots - N w_i \ln N w_i \\&= N \ln N - \{(N w_1 \ln N + N w_2 \ln N + \dots + N w_i \ln N) \\&\quad + (N w_1 \ln w_1 + N w_2 \ln w_2 + \dots + N w_i \ln w_i)\} \\&= N \ln N - \{(w_1 + \dots + w_i) N \ln N + N(w_1 \ln w_1 + \dots + w_i \ln w_i)\}.\end{aligned}$$

With equation 307 this becomes

$$\begin{aligned}\ln W &= -N(w_1 \ln w_1 + w_2 \ln w_2 + \dots + w_i \ln w_i) \\&= -N \sum_{n=1}^{n=i} w_n \ln w_n\end{aligned}\tag{308}$$

where the letter  $n$  denotes any of the numbers from 1 to  $i$ . Equation 308 gives the thermodynamic probability—that is, the number of different possible complexions  $W$  corresponding to the given macroscopic state in which a fraction  $w_1$  of the  $N$  molecules have their representative points falling in the first compartment of phase space, a fraction  $w_2$  have their representative points falling in the second compartment of phase space, and so on.

We now shall determine that distribution,  $w_1, w_2, \dots, w_i$ , of the representative points of the molecules among the different compartments of phase space that will make  $W$  a maximum. This will determine that macroscopic state having the greatest number of complexions and consequently having the maximum thermodynamic probability. It will therefore be the equilibrium state of the substance. Necessarily, when  $W$  is a maximum,  $\delta W = 0$  for small changes of the variables ( $w_1, \dots, w_i$ ), in accordance with the mathematical principles pointed out in article 4. Since it is more convenient to calculate with the logarithm of  $W$  than with  $W$  itself, we shall express the condition for the maximum ( $\delta W = 0$ ) by  $\delta(\ln W) = 0$ . Consequently (eq. 308), since  $N$  is a constant, we have

$$\delta(\ln W) = -N \sum_{n=1}^{n=i} \ln w_n \delta w_n - N \sum_{n=1}^{n=i} \delta w_n = 0.$$

Now by 307 the last sum vanishes; hence our condition becomes

$$\sum_{n=1}^{n=i} \ln w_n \delta w_n = 0.\tag{309}$$

Besides  $\delta(\ln W) = 0$ , we must introduce two other subordinate conditions for determining the equilibrium distribution of the molecules. The first is that the total number  $N$  of molecules in our system is to remain constant; that is,  $\delta N = 0$ . This may be placed in more usable form:

$$\delta N = \delta(N_1 + N_2 + \dots + N_i) = 0,$$

or

$$\delta\left(\frac{N_1}{N} + \frac{N_2}{N} + \dots + \frac{N_i}{N}\right) = 0$$

and

$$\delta(w_1 + w_2 + \dots + w_i) = 0$$

$$\delta w_1 + \delta w_2 + \dots + \delta w_i = 0.$$

Hence

$$\sum_{n=1}^{n=i} \delta w_n = 0. \quad (310)$$

The second subordinate condition is that the total internal energy  $e$  of the system is to remain constant. That is (art. 4)  $\delta e = 0$  for any changes the system might be made to undergo. This may be placed in more usable form if one lets  $\epsilon_1, \epsilon_2, \epsilon_3, \dots, \epsilon_i$  represent the total energy of each molecule in the  $(1, 2, \dots, i)$  compartments in the phase space, respectively. The energy  $\epsilon_n$  associated with a molecule in the  $n$ th phase cell is the sum of its kinetic energy of translation and the interatomic and subatomic energies of the molecule. If we are dealing with a monatomic substance, there will be no interatomic energies, and  $\epsilon_n$  will represent the total kinetic energy of translation of the molecule. We have, then, for the total energy of all the molecules of our substance,

$$e = N_1 \epsilon_1 + N_2 \epsilon_2 + \dots + N_n \epsilon_n + \dots + N_i \epsilon_i$$

since the  $N$ 's represent the number of molecules in the corresponding cells of phase space. Dividing through by the total number of molecules  $N$  and recalling the definition of the  $w$ 's (eq. 306)

$$e = N(w_1 \epsilon_1 + w_2 \epsilon_2 + \dots + w_i \epsilon_i). \quad (311)$$

Recalling that  $N$  is a constant, our condition that  $\delta e = 0$  becomes

$$\delta e = N(\epsilon_1 \delta w_1 + \epsilon_2 \delta w_2 + \dots + \epsilon_i \delta w_i) = 0.$$

Consequently our third condition becomes finally

$$\sum_{n=1}^{n=i} \epsilon_n \delta w_n = 0. \quad (312)$$

Our three conditions for determining equilibrium are then

$$\left. \begin{aligned} \sum_{n=1}^{n=i} \ln w_n \delta w_n &= 0 \\ \sum_{n=1}^{n=i} \epsilon_n \delta w_n &= 0 \\ \sum_{n=1}^{n=i} \delta w_n &= 0. \end{aligned} \right\} \quad (313)$$

We shall now solve this set of three equations simultaneously for  $w_n$  by the method of Lagrange, whose proof and explanation are given in article 5, the standard way of solving such a set of equations. Multiply the second equation by the undetermined constant  $\beta$  and the third by  $\lambda$ . We have

$$\sum_{n=1}^{n=i} \ln w_n \delta w_n + \beta \sum_{n=1}^{n=i} \epsilon_n \delta w_n + \lambda \sum_{n=1}^{n=i} \delta w_n = 0.$$

Combining like terms, we have

$$\sum_{n=1}^{n=i} (\ln w_n + \beta \epsilon_n + \lambda) \delta w_n = 0. \quad (314)$$

By introducing the two undetermined multipliers  $\beta$  and  $\lambda$ , we have enabled all the variations  $\delta w_n$  to be carried out independently of each other in any arbitrary manner; the justification for this statement will be found in article 5. Since the variations  $\delta w_n$  can be carried out independently of each other in any arbitrary manner, the only way equation 314 can remain satisfied at all times and remain equal to zero is for the coefficient of each of the  $\delta w$ 's to vanish. We see, then, that in order to permit any arbitrary changes in the  $\delta w$ 's we must adjust the auxiliary variables  $\beta$  and  $\lambda$  so that the quantity in parentheses will vanish, and consequently equation 314 will remain satisfied at all times. That is,

$$\ln w_n + \beta \epsilon_n + \lambda = 0$$

or

$$w_n = e^{(-\beta \epsilon_n - \lambda)} = e^{-\lambda} e^{-\beta \epsilon_n}.$$

If the constant  $e^{-\lambda}$  is simplified and set equal to  $a$ , we have

$$w_n = ae^{-\beta \epsilon_n}. \quad (315)$$

Both  $\alpha$  and  $\beta$  are constants, obviously independent of  $n$ , and are therefore the same for all the values of  $w_n = w_1, w_2, w_3, \dots$ . They are constants to be determined by the conditions of the particular problem to which equation 315 is applied. If the constant  $\beta$  is positive, as will later be shown to be the case, equation 315 indicates that the fraction or the probability  $w_n$  (that the representative point of a molecule lies in a compartment of the phase space having a large energy  $\epsilon_n$ ) is less than the probability that the representative point lies in a compartment of the phase space having a small energy  $\epsilon_n$ .

The equilibrium distribution of the molecules among the different possible molecular energy states  $\epsilon_n$  is consequently determined by

$$w_n = \alpha e^{-\beta \epsilon_n} \quad (316)$$

with the subordinate condition according to equation 307 for the sum of all the  $w$ 's

$$\sum_{n=1}^{n=i} w_n = \alpha \sum_{n=1}^{n=i} e^{-\beta \epsilon_n} = 1 \quad (317)$$

and also with equation 311 for the total sum  $e$  of all the energies of the molecules,

$$e = N \sum_{n=1}^{n=i} \epsilon_n w_n = N \alpha \sum_{n=1}^{n=i} \epsilon_n e^{-\beta \epsilon_n} \quad (318)$$

since  $\alpha$  is a constant for all the  $w$ 's.

From equation 318 by substituting for  $\alpha$  from 317 we obtain, for the average energy  $\frac{e}{N}$  per molecule, the following expression, which includes the interatomic, the subatomic, and the kinetic energy of translation:

$$\frac{e}{N} = \frac{\sum_{n=1}^{n=i} \epsilon_n e^{-\beta \epsilon_n}}{\sum_{n=1}^{n=i} e^{-\beta \epsilon_n}}. \quad (319)$$

Before we can determine quantitatively the velocities of the different molecules of a vapor in a state of equilibrium at a temperature  $T$ , we must ascertain the relation between the thermodynamic probability  $W$  (that is, the number of possible complexions  $W$  of the given state) and the entropy of the vapor  $s$ . By means of this relation we can evaluate the constants  $\alpha$  and  $\beta$  of equation 316, both of which will be found to involve the temperature  $T$ .

### 50. Relation between the Entropy $s$ and the Thermodynamic Probability $W$

We wish now to determine the relation between the entropy  $s$  of a given macroscopic state and the number of different complexions  $W$  associated with that state. According to the previous article,  $W$  is also referred to as the thermodynamic probability associated with the given macroscopic state.

From the point of view of probability, the state of equilibrium of a system is its most probable state; or it is that macroscopic state whose thermodynamic probability  $W$  is a maximum. Furthermore, when  $W$  is a maximum at a given temperature and pressure, the substance is in the macroscopic state that can be realized by the greatest number of different complexions.

From the point of view of thermodynamics, on the other hand, the state of equilibrium of a substance at a given temperature and pressure is the one whose entropy  $s$  has reached a maximum. Thus the entropy  $s$  is closely similar to the thermodynamic probability  $W$ . As a system approaches equilibrium, both the thermodynamic probability  $W$  and the entropy  $s$  approach a maximum. Consequently (art. 4), when  $s$  and  $W$  have reached a maximum,  $\delta s = 0$  and  $\delta W = 0$  for small changes in the variables determining the state of the system.

Let us next consider two different substances or independent systems having entropies  $s_1$ ,  $s_2$ , and thermodynamic probabilities  $W_1$ ,  $W_2$ , respectively. We wish to determine the relation between the total entropy  $s$  of the two combined systems and the total thermodynamic probability  $W$  of the combination. As will be recalled (art. 19), the total entropy of a system equals the sum of the entropies of its parts; hence

$$s = s_1 + s_2. \quad (320)$$

On the other hand, the total thermodynamic probability  $W$  of the simultaneous existence of specified macroscopic states of two different substances equals the product of the probabilities of the individual macroscopic states; that is,

$$W = W_1 W_2. \quad (321)$$

This is merely the statement of a well-known elementary theorem of probability, found in any college algebra text and given in a different form in article 49, which states that the total probability  $W$  (that both of two independent events will happen together) is the product of their separate probabilities  $W_1$  and  $W_2$ .

By taking the logarithm of both sides, we have

$$\ln W = \ln W_1 + \ln W_2. \quad (322)$$

Comparing equation 322 with 320 one sees that the entropies, as well as the logarithms of the thermodynamic probabilities of the separate systems, are additive. Also, as has been pointed out, both functions are a maximum when the systems are in equilibrium. Consequently, since the entropy  $s$  of a system is proportional to and behaves like the logarithm of thermodynamic probability  $W$  of the system, the following relation appears to exist between the entropy  $s$  of a single system in a particular macroscopic state and the thermodynamic probability  $W$  of that state:

$$s = k \ln W, \quad (323)$$

where  $k$  is a universal constant, later shown to be equal to the gas constant for one molecule.

A somewhat more rigorous derivation of the relation (eq. 323) between the entropy and the thermodynamic probability of any system composed of atoms or molecules may be made as follows. At the start we shall merely assume that the entropy  $s$  is some function  $f(W)$  of the thermodynamic probability  $W$ . In other words, we assume only that there exists some relation between  $s$  and  $W$ . What it is, will be our problem to determine. We have then

$$s = f(W). \quad (324)$$

It must be noticed that  $f$  here denotes not free energy but rather some function  $f(W)$  that depends on  $W$ . We wish now to determine the form of  $f(W)$ . Suppose we have two entirely independent and separate systems whose entropies are  $s_1$  and  $s_2$  and whose thermodynamic probabilities are  $W_1$  and  $W_2$ . It then follows for the first and second system, respectively, that

$$\left. \begin{aligned} s_1 &= f(W_1), \\ s_2 &= f(W_2). \end{aligned} \right\} (325)$$

Let us now combine the two systems. The total thermodynamic probability  $W$  of the two systems taken together as a single unit is the product  $(W_1 W_2)$ . This follows because to each of the  $W_1$  complexions of the first system, there are  $W_2$  of the second. Consequently, the total number of complexions of the two independent systems, taken together as one, must be  $(W_1 W_2)$ . The same result follows from the theorem of probability just previously mentioned.

Now the total entropy  $s$  of the two systems combined equals the sum of the entropies  $s_1$  and  $s_2$  of the separate ones. From equations 320, 324, and 321, we have then

$$s = s_1 + s_2 = f(W) = f(W_1 W_2); \quad (326)$$

and from equations 325 and 326, using the second and fourth member of 326,

$$f(W_1) + f(W_2) = f(W_1 W_2).$$

Differentiating this equation with respect to  $W_1$ , we have

$$\frac{df(W_1)}{dW_1} + \frac{df(W_2)}{dW_1} = \frac{df(W_1 W_2)}{dW_1}. \quad (327)$$

From a well-known theorem on differentiation, we may write for the last term of equation 327

$$\frac{df(W_1 W_2)}{dW_1} = \frac{df(W_1 W_2)}{d(W_1 W_2)} \frac{d(W_1 W_2)}{dW_1} = \frac{d(W_1 W_2)}{dW_1} \frac{df(W_1 W_2)}{d(W_1 W_2)} = W_2 \frac{df(W_1 W_2)}{d(W_1 W_2)};$$

and since  $f(W_2)$  is independent of  $W_1$ , the first system being independent of the other, the second term of 327 is zero, so that equation 327 becomes with the above

$$\frac{df(W_1)}{dW_1} = W_2 \frac{df(W_1 W_2)}{d(W_1 W_2)}. \quad (328)$$

Differentiating the same equation in like manner, but with respect to  $W_2$ , we have, corresponding to equation 328,

$$\frac{df(W_2)}{dW_2} = W_1 \frac{df(W_1 W_2)}{d(W_1 W_2)}. \quad (329)$$

Multiplying equations 328 and 329 by  $W_1$  and  $W_2$ , respectively, we find that their right-hand members are identical. Hence

$$W_1 \frac{df(W_1)}{dW_1} = W_2 \frac{df(W_2)}{dW_2} = W_1 W_2 \frac{df(W_1 W_2)}{d(W_1 W_2)}. \quad (330)$$

Since the two systems were assumed to be entirely separate and independent of each other, any variation of  $W_1$  can be carried out independently, with no relation to the changes in  $W_2$ . Now the first member of equation 330 is a function of  $W_1$  only and is therefore completely unaffected by changes of  $W_2$ , whereas the second or middle member is a function of  $W_2$  only and is completely unaffected by changes of  $W_1$ . The only way for such a state of affairs to exist, where both members of the equation are always equal to each other yet depend on entirely different variables, is

for both members of the equation to equal one and the same constant, which we shall here call  $k$ . Thus

$$W_1 \frac{df(W_1)}{dW_1} = k,$$

and

$$W_2 \frac{df(W_2)}{dW_2} = k.$$

For the type of systems with which we are dealing,  $k$  is a universal constant, the same for all systems, no matter of what type. Obviously it is immaterial which of these equations we integrate. Both will yield an integral of the same final form. Let us therefore drop the subscripts 1 and 2. We have

$$df(W) = k \frac{dW}{W}.$$

Integrating, we now obtain the exact form of the originally unknown function  $f(W)$ . It is

$$f(W) = k \ln W + C. \quad (331)$$

Recalling from 324 that  $s$  was assumed to be a function of  $W$ , we find that equation 331 becomes

$$s = k \ln W + C. \quad (332)$$

To evaluate  $C$  let us note the conditions at absolute zero where there is no motion of the molecules and where all molecules are therefore in the same cell in the phase space where the energy of each molecule is zero. Then  $W$ , the number of complexions of the system, has a value of 1 at absolute zero, and therefore  $\ln W = 0$  at absolute zero. Since (eq. 90)  $s$  is also zero at this temperature,  $C$  must be equal to zero; and therefore we may write

$$s = k \ln W. \quad (333)$$

This equation, the same we found previously by a less rigorous approach, determines the desired relation between the entropy  $s$  and the thermodynamic probability  $W$ , where  $k$  is a universal constant because it is the same for all systems. The only two assumptions made in obtaining 333 were, first, the idea that the total entropy  $s$  of a system was equal to the sum of the entropies  $s_1, s_2, \dots$  of its parts; and, second, the fundamental theorem of probability previously given in connection with equation 321. Both these assumptions are substantiated by all available evidence.

51. Relation between the Entropy  $s$  of a System at Equilibrium and the Internal Energy  $\epsilon_n$  of the Different Molecules

We can now show how the entropy  $s$  of the system depends on the distribution  $w_n$  of the molecules among the different possible energy states  $\epsilon_n$  in which a molecule of the system might find itself. From equation 308, we had

$$\ln W = -N \sum_{n=1}^{n=i} w_1 \ln w_1 + w_2 \ln w_2 + \dots = -N \sum_{n=1}^{n=i} w_n \ln w_n.$$

Inserting this in equation 333 above, we have

$$s = -kN \sum_{n=1}^{n=i} w_n \ln w_n. \quad (334)$$

But from equation 316

$$w_n = ae^{-\beta\epsilon_n};$$

hence

$$\ln w_n = (-\beta\epsilon_n + \ln a) = -(\beta\epsilon_n - \ln a).$$

Therefore 334 becomes

$$s = kN \sum_{n=1}^{n=i} w_n (\beta\epsilon_n - \ln a).$$

or

$$s = kN \sum_{n=1}^{n=i} (\beta w_n \epsilon_n - w_n \ln a).$$

Splitting this into the two series and recalling from the statements made in connection with equation 315 that  $\beta$  and  $a$  are constants independent of  $n$ ,

$$s = kN\beta \sum_{n=1}^{n=i} w_n \epsilon_n - kN \ln a \sum_{n=1}^{n=i} w_n.$$

From equations 307 and 311 we had, respectively, that

$$\sum_{n=1}^{n=i} w_n = 1,$$

and

$$N \sum_{n=1}^{n=i} w_n \epsilon_n = e$$

where  $e$  denotes the total internal energy of the system. Hence the expression for the entropy  $s$  becomes

$$s = k\beta e - kN \ln a.$$

Again from equation 317 we had

$$\alpha \sum_{n=1}^{n=i} e^{-\beta \epsilon_n} = 1,$$

or

$$\alpha = \frac{1}{\sum_{n=1}^{n=i} e^{-\beta \epsilon_n}}$$

so that

$$\ln \alpha = -\ln \sum_{n=1}^{n=i} e^{-\beta \epsilon_n}.$$

With this, the expression for  $s$  becomes

$$s = k \beta e + kN \ln \sum_{n=1}^{n=i} e^{-\beta \epsilon_n}. \quad (335)$$

## 52. Relation of the Temperature to the Distribution $w_n$ of the Molecules among the Different Possible Energy States $\epsilon_n$

A statement of the First Law of thermodynamics is given by equation 47 as

$$de = dq - dw. \quad (336)$$

Now if the only work  $w$  done is that of expansion against an external pressure, equation 336 becomes

$$de = dq - p dv. \quad (337)$$

For reversible processes the Second Law (eq. 70) permits us to write equation 337 in the following form:

$$de = T ds - p dv. \quad (338)$$

Solving equation 338 for  $ds$ , we have

$$ds = \left(\frac{1}{T}\right) de + \left(\frac{p}{T}\right) dv. \quad (339)$$

Let us now obtain another expression for  $ds$ . As already pointed out (art. 2), the state of a simple system is determined by two variables, and these might be any such pairs as either  $T$  and  $v$ , or  $e$  and  $v$ . Let us use

the pair  $e$  and  $v$  to describe the state of the system. Then the entropy  $s$  of the system is a function of these two variables. Purely as a mathematical consequence (art. 1 and 2), we have

$$ds = \left( \frac{\partial s}{\partial e} \right)_v de + \left( \frac{\partial s}{\partial v} \right)_e dv. \quad (340)$$

Equations 339 and 340 are merely two ways of stating the same dependence of  $ds$  upon  $de$  and  $dv$ . Hence, equating the coefficients of  $de$  and  $dv$  in equations 339 and 340, we have

$$\left( \frac{\partial s}{\partial e} \right)_v = \frac{1}{T} \quad \left. \right\} \quad (341)$$

and

$$\left( \frac{\partial s}{\partial v} \right)_e = \frac{p}{T}. \quad \left. \right\}$$

We shall now use these general thermodynamic expressions for evaluating  $\beta$  in the distribution function  $w_n$  of equation 316; but first we must transform equation 335, which was

$$s = k \beta e + kN \ln \left( \sum_{n=1}^{n=i} e^{-\beta \epsilon_n} \right), \quad (342)$$

into a form such that we can substitute the result for  $\frac{1}{T}$  in the first of equations 341. Remembering that  $k$ ,  $N$ , and the energy  $\epsilon_n$  associated with a molecule in the  $n$ th compartment of phase space are constants, independent of all changes made in the system itself so long as the total number of molecules  $N$  in the system remains the same; and remembering further that the internal energy  $e$  depends on  $\beta$ , according to equation 319, we find upon differentiating equation 342 with respect to  $\beta$ ,

$$\left( \frac{\partial s}{\partial \beta} \right)_v = ke + k\beta \left( \frac{\partial e}{\partial \beta} \right)_v - \frac{kN \sum_{n=1}^{n=i} \epsilon_n e^{-\beta \epsilon_n}}{\sum_{n=1}^{n=i} e^{-\beta \epsilon_n}}. \quad (343)$$

From equation 319 it will be recalled that

$$e = N \frac{\sum_{n=1}^{n=i} \epsilon_n e^{-\beta \epsilon_n}}{\sum_{n=1}^{n=i} e^{-\beta \epsilon_n}}.$$

Substituting this for the summation expressions in equation 343, we have

$$\left( \frac{\partial s}{\partial \beta} \right)_v = k \beta \left( \frac{\partial e}{\partial \beta} \right)_v. \quad (344)$$

Now, by a mathematical theorem on partial differentiation proved in article 6,

$$\left( \frac{\partial e}{\partial \beta} \right)_v = \frac{1}{\left( \frac{\partial \beta}{\partial e} \right)_v}.$$

Equation 344 therefore becomes

$$\left( \frac{\partial s}{\partial \beta} \right)_v \left( \frac{\partial \beta}{\partial e} \right)_v = k \beta.$$

It was shown (art. 7) that we may write

$$\left( \frac{\partial s}{\partial \beta} \right)_v \left( \frac{\partial \beta}{\partial e} \right)_v = \left( \frac{\partial s}{\partial e} \right)_v,$$

so that the preceding equation becomes

$$\left( \frac{\partial s}{\partial e} \right)_v = k \beta,$$

from which (by eq. 341) we get

$$k \beta = \frac{1}{T}, \quad \text{or} \quad \beta = \frac{1}{kT}. \quad (345)$$

We can now express the distribution function  $w_n$  of equation 316 in terms of the universal constant  $k$ , often called Boltzman's constant—that is, the gas constant per molecule (art. 59)—and of the temperature  $T$ . From equation 316 we had

$$w_n = a e^{-\beta \epsilon_n},$$

which now becomes

$$w_n = a e^{-\frac{\epsilon_n}{kT}}. \quad (346)$$

Equation 346 gives the fraction  $w_n$  of the total number of molecules  $N$

of the system that have an energy  $\epsilon_n$  when the whole system is at the uniform temperature  $T$  throughout. Thus, though the system is at the temperature  $T$  throughout, the energy of the individual molecules  $\epsilon_n$  varies widely among the different molecules.

### 53. Relation of the Entropy $s$ and the Maximum Work $a$ , of the System, to the Energies $\epsilon_n$ of the Individual Molecules of the System

From equation 335 we have for the entropy  $s$  of the system

$$s = k \beta e + kN \ln \left( \sum_{n=1}^{n=i} e^{-\beta \epsilon_n} \right),$$

which by equation 345 becomes

$$s = \frac{e}{T} + kN \ln \left( \sum_{n=1}^{n=i} e^{-\frac{\epsilon_n}{kT}} \right) \quad (347)$$

and defines the specific entropy  $s$  of the system composed of  $N$  molecules in terms of the energies of the individual molecules  $\epsilon_n$ , the total internal energy  $e$ , and the temperature  $T$  of the system.

As will be recalled (eq. 279), the maximum work,  $a$ , was defined by

$$a = e - Ts.$$

Introducing the value of  $s$  from this into equation 347, we find, upon solving for  $a$ ,

$$a = -kNT \ln \left( \sum_{n=1}^{n=i} e^{-\frac{\epsilon_n}{kT}} \right), \quad (348)$$

showing, in the same manner as equation 335 for the entropy, the dependence of the maximum work  $a$  on the energies  $\epsilon_n$  of the individual molecules of the system.

Now, to demonstrate the consistency of the expressions developed in this section on kinetic theory, including the relation between  $s$  and  $W$  given by equation 333, we will show that the Gibbs-Helmholtz equation, a fundamental equation of thermodynamics, can be derived from equation 348 for the maximum work function  $a$ . The Gibbs-Helmholtz equation (eq. 284) is

$$e = a - T \left( \frac{\partial a}{\partial T} \right)_{v, w_m}$$

Differentiating  $a$  in equation 348, while maintaining all the other variables except  $T$  constant, we have

$$\frac{\partial a}{\partial T} = -kN \ln \left( \sum_{n=1}^{n=i} e^{-\frac{\epsilon_n}{kT}} \right) - kNT \frac{\sum_{n=1}^{n=i} \left( \frac{\epsilon_n}{kT^2} \right) e^{-\frac{\epsilon_n}{kT}}}{\sum_{n=1}^{n=i} e^{-\frac{\epsilon_n}{kT}}}.$$

Simplifying the last term,

$$\frac{\partial a}{\partial T} = -kN \ln \left( \sum_{n=1}^{n=i} e^{-\frac{\epsilon_n}{kT}} \right) - \frac{N}{T} \frac{\sum_{n=1}^{n=i} \epsilon_n e^{-\frac{\epsilon_n}{kT}}}{\sum_{n=1}^{n=i} e^{-\frac{\epsilon_n}{kT}}}.$$

Multiplying through by  $T$ ,

$$T \frac{\partial a}{\partial T} = -kNT \ln \left( \sum_{n=1}^{n=i} e^{-\frac{\epsilon_n}{kT}} \right) - N \frac{\sum_{n=1}^{n=i} \epsilon_n e^{-\frac{\epsilon_n}{kT}}}{\sum_{n=1}^{n=i} e^{-\frac{\epsilon_n}{kT}}}.$$

The first term on the right side of the equation is immediately recognized to be nothing but the maximum work,  $a$ , according to equation 348; and the second is, according to equation 319 as modified by equation 345, the negative of the total internal energy  $e$  of the system. The whole then simplifies down to

$$T \frac{\partial a}{\partial T} = a - e,$$

which, rearranged, gives us directly the desired Gibbs-Helmholtz expression

$$e = a - T \frac{\partial a}{\partial T}. \quad (349)$$

#### 54. Maxwell Distribution of Molecular Velocities

We shall use equation 315 in determining the speeds of translation possessed by the different molecules of a gas or vapor. Actually we shall determine the expression for the fraction  $w_n$  of the total number of molecules  $N$  having a given specified speed. This expression will be used later in discussing the speeds of the different molecules moving normally to the air-water interface of soil moisture.

Let us express the total energy  $\epsilon_n$  of a molecule of an ideal gas as the

sum of its kinetic energy of translation  $\epsilon_n'$  and its internal energy  $\epsilon_n''$  so that

$$\epsilon_n = \epsilon_n' + \epsilon_n''.$$

Then the fraction  $w_n$  of the total number of molecules whose representative points fall in the  $n$ th compartment or cell of the multidimensional phase space is given by equation 315, together with 345,

$$w_n = ae^{-\frac{\epsilon_n'}{kT} - \frac{\epsilon_n''}{kT}}. \quad (350)$$

As pointed out earlier (art. 49), if the molecule has  $d$  degrees of freedom, the phase space has  $2d$  dimensions. The first  $d$  dimensions describe the instantaneous position of the center of mass of the molecule, which we represent by  $x, y$ , and  $z$ , as well as the position of the parts of the molecule with respect to its center of mass, which we represent by  $x_1, x_2, x_3, \dots, x_{d-3}$ . The other  $d$  dimensions describe the velocity of translation of the center of mass, which we represent by  $u_x, u_y$ , and  $u_z$ , as well as the movements of the parts of the molecule with respect to its center of mass, which we represent by  $u_1, u_2, u_3, \dots, u_{d-3}$ . Let us divide the phase space into compartments, all of equal volume, whose amount we shall call  $g$ . We then have

$$g = (dx dy dz dx_1 dx_2 \dots dx_{d-3}) (du_x du_y du_z du_1 du_2 \dots du_{d-3}). \quad (351)$$

It may seem strange at first to speak of the multidimensional element  $g$  as an element of volume. Although ordinarily it seems impossible to visualize a volume of more than three dimensions, we are, as previously mentioned, not handicapped by any such limitation in mathematics, where we can deal with a space of as many dimensions as we please. Since these multidimensional spaces have properties analogous to the three-dimensional spaces of ordinary experience, we often apply many of the terms associated with the latter to the former.

Multiplying the denominator and numerator of equation 350 by  $g$  and its equivalent, respectively, according to equation 351, and recalling that the kinetic energy of translation is  $\epsilon_n' = \frac{1}{2} mu^2$  where

$$u^2 = u_x^2 + u_y^2 + u_z^2,$$

we have

$$w_n = \frac{a}{g} e^{-\frac{\epsilon_n''}{kT}} e^{-\frac{mu^2}{2kT}} (dx dy dz dx_1 dx_2 \dots) (du_x du_y du_z du_1 du_2 \dots).$$

This equation may be restated as

$$w_n = \frac{a}{g} e^{-\frac{\epsilon_n'}{kT}} (dx_1 dx_2 \dots du_1 du_2 \dots) (dx dy dz) e^{-\frac{mu^2}{2kT}} (du_x du_y du_z). \quad (352)$$

As already mentioned (eq. 306),  $w_n$  gives the fraction of the total number of molecules having an energy  $\epsilon_n$  whose representative points fall in the  $n$ th compartment or cell of phase space having the volume  $g$ .

What we are now really seeking is an expression for the fraction  $w'_n$ , of the total number of molecules, having a translational velocity  $u$ , whose components lie between  $u_x$  and  $u_x + du_x$ ,  $u_y$  and  $u_y + du_y$ , and  $u_z$  and  $u_z + du_z$ , no matter what their internal energies  $\epsilon_n''$  might be. Since the internal energies are entirely independent of the velocities of translation  $u_x, u_y, u_z$ , we may integrate or sum the first exponential of equation 352 (entirely independently of the second) over all dimensions in the phase space except those corresponding to  $u_x, u_y, u_z$ . We then obtain

$$w'_n = \left[ \frac{a}{g} \int e^{-\frac{\epsilon_n''}{kT}} (dx_1 dx_2 \dots du_1 du_2 \dots) (dx dy dz) \right] e^{-\frac{mu^2}{2kT}} du_x du_y du_z.$$

Denoting the constant within the brackets, obtained after the integration, by  $a'$  and recalling that  $u^2 = u_x^2 + u_y^2 + u_z^2$ , we have

$$w'_n = a' e^{-\frac{m}{2kT}(u_x^2 + u_y^2 + u_z^2)} du_x du_y du_z. \quad (353)$$

We may determine  $a'$  by recalling (eq. 307) the condition that

$$\sum_{n=1}^{n=i} w'_n = 1.$$

We have

$$\sum_{n=1}^{n=i} w'_n = a' \int_{-\infty}^{\infty} e^{-\frac{mu_x^2}{2kT}} du_x \int_{-\infty}^{\infty} e^{-\frac{mu_y^2}{2kT}} du_y \int_{-\infty}^{\infty} e^{-\frac{mu_z^2}{2kT}} du_z = 1,$$

since components of velocity may be either positive or negative. Using the formula for the definite integral given by equation 37, this reduces after integration so that we have

$$a' \left( \frac{2kT \pi}{m} \right)^{\frac{3}{2}} = 1$$

and therefore

$$a' = \left( \frac{m}{2kT\pi} \right)^{\frac{3}{2}}.$$

Then, upon recalling the definition of  $w'_n$ , equation 353 becomes, with the above and equation 306,

$$w'_n = \frac{N_n}{N} = \left( \frac{m}{2\pi kT} \right)^{\frac{3}{2}} e^{-\frac{mu^2}{2kT}} du_x du_y du_z.$$

From this we obtain immediately Maxwell's law giving the number of molecules  $N_n$  (which we shall now denote by  $dN$ ) having components of velocity lying between  $u_x$  and  $u_x + du_x$ ,  $u_y$  and  $u_y + du_y$ ,  $u_z$  and  $u_z + du_z$ . Substituting  $dN$  for  $N_n$  in the equation above and solving for  $dN$ , we have

$$dN = N \left( \frac{m}{2\pi kT} \right)^{\frac{3}{2}} e^{-\frac{m}{2kT}(u_x^2 + u_y^2 + u_z^2)} du_x du_y du_z. \quad (354)$$

Suppose we now consider only one of the components of velocity of the molecules, such as  $u_x$  along the  $x$  axis, and ask how  $dN$  depends on the velocity  $u_x$ . That is, we wish to find out how many molecules  $dN$  have

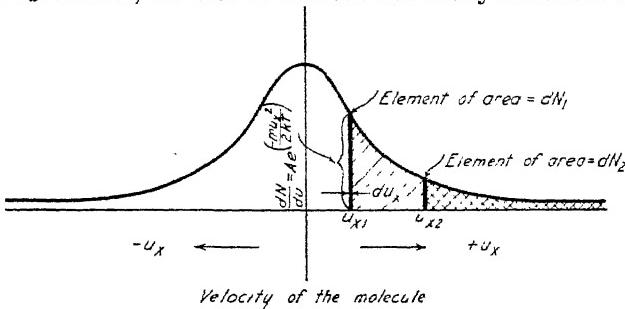


Fig. 28.—Distribution of the components of the velocities of the molecules along any one direction in space. Area under curve between any two abscissas  $u_{x1}$  and  $u_{x2}$  gives the number of molecules having velocities between  $u_{x1}$  and  $u_{x2}$ .

a value for the  $x$  component of their velocity falling between  $u_x$  and  $u_x + du_x$ . To answer this, we shall integrate equation 354 over all molecules with respect to  $u_y$  and  $u_z$ :

$$dN = A e^{-\frac{m}{2kT} u_x^2} du_x \quad (355)$$

where  $A$  is the constant obtained after the integration has been performed. If we plot the coefficient of  $du_x$  of equation 355 against  $u_x$  (fig. 28), we get the well-known Gaussian form of distribution curve. This is symmetrical; that is, as many molecules  $dN$  in the vapor have a given velocity  $+u_x$  in one direction as have a velocity  $-u_x$  in the opposite. Also, very few molecules have great velocity; and many have no  $x$  component of velocity at all. The expressions for the distribution of velocities along the  $y$  and  $z$  axes have the same form as equation 355.

##### 55. Velocities of Molecules Normal to Vapor-Liquid Interface as Related to Vapor Pressure

Equation 355 applies directly to the problem, considered to some extent in article 47, of the outward emission of water molecules from the liquid films surrounding soil particles. In this case we are interested only

in half of the curve—that is, only in the molecules moving outward from the film. If no adsorptive forces surrounded the soil particle, all the molecules of the ( $+u_z$ ) part of the curve (fig. 28) would leave the moisture film. Since, however, there are adsorptive forces, the water molecules must possess a certain definite minimum kinetic energy in order to escape into the vapor phase. This will entail a minimum velocity  $u_{z1}$ . All molecules in the layer having a velocity less than  $u_{z1}$  will be held back in the liquid surface, but all those having a velocity greater will escape; that is, the faster molecules escape, while the slower ones are held behind.

As the moisture content of the soil is decreased, the vapor-liquid interface comes more and more under the influence of the adsorptive forces surrounding the soil particle, so that the molecule must possess more and more kinetic energy in order to escape. Consequently, the minimum velocity required will be increased to some other velocity (for example,  $u_{z2}$ ); and only those molecules in the liquid layer having velocities greater than this will escape.

The curve (fig. 28) should be so constructed that the area under it between two velocities such as  $u_{z1}$  and  $u_{z2}$  gives the total number of molecules having velocities within the velocity interval ( $u_{z2} - u_{z1}$ ). Also the area under the curve to the right of some velocity value such as  $u_{z1}$  and extending out to infinity gives the total number of molecules having a velocity greater than  $u_{z1}$ .

Figure 28, based on the Maxwell distribution law, is the basis for predicting how changes of moisture content will affect the vapor pressure of soil moisture. When the soil is saturated, all the molecules whose numbers are represented by the area of the positive half of the figure escape into the vapor phase, being beyond the influences of the soil forces. When the soil-moisture content is decreased from a state of saturation the molecules begin to require, in order to escape into the vapor phase, a certain minimum amount of kinetic energy which depends upon the moisture content. If the moisture content has been decreased so that an amount of kinetic energy  $\frac{1}{2}mu_{z1}^2$  is necessary for escape, then all the molecules whose number is represented by the entire area under the curve to the right of  $u_{z1}$  will escape into the vapor phase, and all the rest will remain in the liquid. If the soil moisture content is further decreased so that at least an amount of kinetic energy  $\frac{1}{2}mu_{z2}^2$  is required for the escape, then only those molecules whose number is represented by the entire area under the curve to the right of  $u_{z2}$  will escape into the vapor phase, and this area is seen to be less than that corresponding to a higher moisture content. Thus as the soil moisture content is decreased, more and more molecules having positive  $u_z$  components of velocity are held back in the liquid, and fewer and fewer can go into the vapor phase.

No matter how dry the soil or how tightly the soil moisture is bound to the soil particle, there will always be a few molecules with a high enough velocity and therefore with sufficient kinetic energy to escape. As the soil moisture content approaches zero, the vapor pressure of the soil moisture thus decreases gradually; but it cannot become zero until the soil moisture content is also zero.

The Maxwell distribution law also explains why a moist surface placed in an atmosphere whose humidity is below 100 per cent tends to cool off. Experimentally we find that the lower the humidity and the greater the wind movement, the greater is the cooling effect. The explanation is that

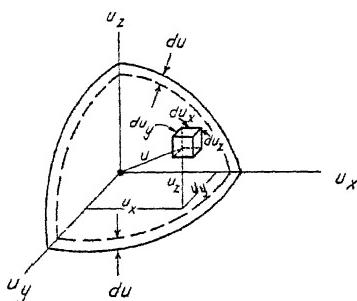


Fig. 29.—Element of volume in phase space.

the temperature of an object is determined entirely by the mean kinetic energy of all the molecules composing it. As this energy is decreased, the temperature also decreases. Now, as was just shown, only the fastest-moving molecules can escape from the liquid and be carried away by the air currents. Thus those remaining behind have a smaller average velocity, a smaller mean kinetic energy, and therefore a lower temperature. Hence evaporation from a moist surface tends to cool it off.

If the space above the liquid is saturated, just as many fast molecules move out of the liquid in a given time as move into it. In this latter case, accordingly, there is no cooling effect.

#### • 56. Number of Molecules Having Speeds within Certain Limits

In article 54 we considered the number of molecules  $dN$  having components of velocity  $u_x$  in any single direction within the velocity interval between  $u_x$  and  $u_x + du_x$ . We considered the same also for the  $y$  and  $z$  axes. Now, going a bit further, we shall determine the number of molecules  $dN$  having speeds within the interval between  $u$  and  $u + du$  without regard to direction of movement of the molecule. Thus the three compo-

nents of velocity may vary in any arbitrary manner so long as they satisfy the equation

$$u^2 = u_x^2 + u_y^2 + u_z^2,$$

and  $u$  lies within the velocity interval between  $u$  and  $u + du$ . Thus the element of volume  $du_x, du_y, du_z$  in the velocity space as given by equation 354 may be replaced by the volume included between the two concentric spheres of radii  $u$  and  $u + du$ , an octant of which is shown in figure 29. This is possible, since all the molecules whose representative points fall within the same spherical shell have the same speed  $u$  and therefore the same value for the total kinetic energy  $\frac{1}{2}mu^2$  in the exponential of the

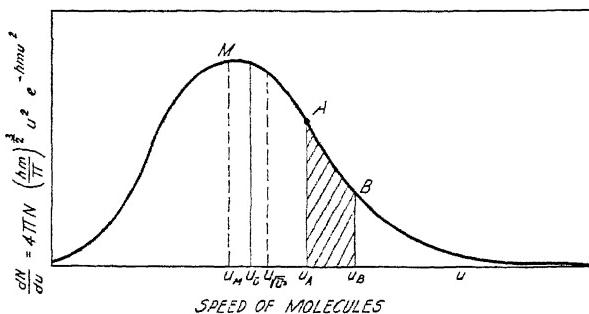


Fig. 30.—Speed distribution of molecules.

distribution function, even though their components of velocity  $u_x, u_y, u_z$  may be widely different. The volume of the spherical shell included between the concentric spheres of radii  $u$  and  $u + du$  is immediately seen to be  $4\pi u^2 du$ . We shall therefore replace the cubical volume element of integration  $du_x, du_y, du_z$  by this spherical shell. Equation 354 then becomes

$$dN = 4\pi N \left( \frac{m}{2\pi kT} \right)^{3/2} u^2 e^{-\frac{mu^2}{2kT}} du.$$

To simplify this, let us set  $\frac{1}{2kT} = h$ . Obviously,  $h$  is the same for all molecules and is independent of  $u$ . We have then

$$dN = 4\pi N \left( \frac{hm}{\pi} \right)^{3/2} u^2 e^{-hmu^2} du. \quad (356)$$

Let us plot the coefficient of  $du$  of equation 356 against  $u$  as shown in figure 30. The area under any segment of the curve equals the number of molecules having speeds whose values lie between those represented by

the abscissas of the limits of the segment. Thus, for example, the number of water-vapor molecules, in a container at a temperature  $T$ , whose speeds lie between  $u_A$  and  $u_B$ , is given by the shaded area under the segment  $AB$ . There is no negative half of the curve, since we are here interested only in the absolute magnitudes of the velocities, not in their direction. Also the distribution curve will be found to extend asymptotically out to  $u = +\infty$ ; but since the area under the portion of the curve representing high velocities is negligible, the number of molecules having these high speeds must also be negligible. This curve for the distribution of speeds  $u$  contrasts greatly with figure 28, for the distribution of velocities of one of the three components of  $u$ . In figure 28 the curve is symmetrical with respect to the vertical axis; in figure 30, it is not.

### 57. Dependence of Temperature on the Root-Mean-Square Speeds of Molecules

As mentioned previously, the temperature of a substance is determined entirely by the kinetic energy of the molecules; and the kinetic energy of a molecule equals  $\frac{1}{2}mu^2$ . Since the molecules of a substance have widely different velocities, we see that in order to express the temperature or the internal energy of the gas in terms of the kinetic energy of the individual molecules we must find the average of the squares of the velocities (which we shall denote by  $\bar{u^2}$ ) of all the molecules. The formula for the average of all the  $u^2$ 's associated with the different molecules is, according to the definition of  $\bar{u^2}$ ,

$$\bar{u^2} = \frac{\int_0^\infty u^2 dN}{N},$$

which with equation 356 becomes

$$\bar{u^2} = 4\pi \left(\frac{h m}{\pi}\right)^{\frac{3}{2}} \int_0^\infty u^4 e^{-\frac{h m u^2}{k T}} du.$$

Integrating this by means of the expression given for the definite integral in equation 40, we have for the average of the squares of the velocities of all the molecules

$$\bar{u^2} = \frac{3}{2 h m} = \frac{3 k T}{m},$$

since  $h$  was set equal to  $\frac{1}{2 k T}$ . From this we have for the average kinetic

energy of a molecule,

$$\frac{m \bar{u^2}}{2} = \frac{3}{2} k T. \quad (357)$$

This shows that as the average kinetic energy of the molecules of a substance increases, the temperature  $T$  of the substance must also increase, since  $k$  is a universal constant which, as will be shown (art. 59), is the well-known gas constant per molecule. The position of the root-mean-square speed  $\sqrt{\bar{u}^2}$  with respect to the maximum  $M$  of the distribution curve is shown in figure 30. As shown, the root-mean-square speed  $\sqrt{\bar{u}^2}$  is greater than the most probable velocity  $u_M$ .

### 58. Average Speed of Molecules

We have just been considering the root-mean-square speed of the molecules denoted by  $\sqrt{\bar{u}^2}$ . We shall now determine their average speed, which we shall denote by  $\bar{u}$ . By definition it is

$$\bar{u} = \frac{\int_0^\infty u dN}{N}, \quad (358)$$

and with 356 it becomes

$$= \frac{4\pi N \left(\frac{h m}{\pi}\right)^{\frac{3}{2}} \int_0^\infty u^3 e^{-\hbar m u^2} du}{N}$$

or

$$= 2\pi \left(\frac{h m}{\pi}\right)^{\frac{3}{2}} \int_0^\infty u^2 e^{-\hbar m u^2} du^2,$$

putting  $u^2 = x$  in order to transform it into the familiar integral form

$$= 2\pi \left(\frac{h m}{\pi}\right)^{\frac{3}{2}} \int_0^\infty x e^{-\hbar m x} dx,$$

which can be found in any table of integrals and works out to be

$$\bar{u} = 2\pi \left(\frac{h m}{\pi}\right)^{\frac{3}{2}} \frac{1}{(h m)^2} = \frac{2}{\sqrt{\pi h m}} = 2 \sqrt{\frac{2kT}{\pi m}}. \quad (359)$$

The position of the mean or average speed  $\bar{u}$  with respect to the root-mean-square  $\sqrt{\bar{u}^2}$  and the maximum  $M$  of the distribution curve is shown in figure 30.

### 59. Equation of State of an Ideal Gas and the Gas Constant $k$ per Molecule

In the previous articles, on a purely statistical foundation based upon considerations of probability, we have arrived at several expressions describing the energy relations among the individuals of an assemblage of

molecules. No experimental data were used. On the basis of these expressions there was derived, in article 54, the Maxwell distribution law for molecular velocities, whose validity has been thoroughly substantiated by experiment. We shall now show that the ideal gas law also follows as a natural consequence from these statistical considerations. In so doing we shall make use of

$$p = - \left( \frac{\partial a}{\partial v} \right)_T, \quad (360)$$

which is obtained from equation 280 when the only work done is that of expansion against an external pressure, so that  $dw = pdv$ , and equation 348, which is

$$a = -kNT \ln \sum_{n=1}^{n=i} e^{-\frac{\epsilon_n}{kT}}. \quad (361)$$

Let us consider an ideal polyatomic gas. Each molecule will then possess not only three degrees of freedom in translation, but also certain others often called internal degrees of freedom, such as vibration and rotation of the parts of the molecule. Let  $\epsilon_n'$ , as before, denote the kinetic energy of translation of a molecule whose representative point lies in the  $n$ th compartment of the phase space; and let  $\epsilon_n''$  be its corresponding internal energy. Then the total energy of the molecule, as pointed out previously, is

$$\epsilon_n = \epsilon_n' + \epsilon_n''. \quad (362)$$

As previously pointed out (art. 49), if the molecule has  $d$  degrees of freedom, the corresponding phase space will have  $2d$  dimensions: one set of  $d$  dimensions describes the instantaneous position of the parts of the molecule, while the other set of  $d$  dimensions describes the movements of the corresponding parts. The phase space is then divided up into compartments, all of equal volume, whose amount we shall call  $g$  (eq. 351). If  $u_x, u_y, u_z$  represent the components of the velocity of translation of the molecule whose instantaneous coördinates of position are  $x, y, z$  and if  $u_1, u_2, \dots$  and  $x_1, x_2, \dots$  represent in like manner the movements and coördinates of position associated with the internal degrees of freedom of the molecule, we have, for the volume of each compartment or cell of phase space,

$$g = (du_x du_y du_z dx dy dz) (du_1 du_2 \dots; dx_1 dx_2 \dots).$$

There are, of course,  $d$  dimensions of the type  $(u_x, u_y, u_z; u_1, u_2, \dots)$ , and  $d$  of the type  $(x, y, z; x_1, x_2, \dots)$ , making  $2d$  dimensions in all. The coordinates

$u_x u_y u_z; xyz$  determine  $\epsilon_n'$ , and the coördinates  $u_1 u_2 \dots; x_1 x_2 \dots$  determine  $\epsilon_n''$ .

Let us now proceed to evaluate the summation found in equation 361. According to 362 the summation becomes

$$\sum_{n=1}^{n=i} e^{-\frac{\epsilon_n'}{kT} - \frac{\epsilon_n''}{kT}}.$$

This summation is to be carried out over all the  $i$  cells or small compartments, whose volume is  $g$ , of phase space. The summation may most easily be carried out by converting it into an integration over all the  $i$  cells, as follows:

$$\sum_{n=1}^{n=i} e^{-\frac{\epsilon_n'}{kT} - \frac{\epsilon_n''}{kT}} =$$

$$\frac{1}{g} \iint \dots \int e^{-\frac{\epsilon_n'}{kT}} du_x du_y du_z dx dy dz \iint \dots \int e^{-\frac{\epsilon_n''}{kT}} du_1 du_2 \dots dx_1 dx_2 \dots \quad (363)$$

We shall now evaluate the first integral. Since we are dealing with an ideal polyatomic gas in which there are no forces between the molecules, the translational energy  $\epsilon_n'$  of a molecule may be represented by

$$\epsilon_n' = \frac{m}{2} (u_x^2 + u_y^2 + u_z^2),$$

so that

$$\begin{aligned} & \frac{1}{g} \iint \dots \int e^{-\frac{\epsilon_n'}{kT}} du_x du_y du_z dx dy dz \\ &= \frac{1}{g} \int_{-\infty}^{\infty} e^{-\frac{mu_x^2}{2kT}} du_x \int_{-\infty}^{\infty} e^{-\frac{mu_y^2}{2kT}} du_y \int_{-\infty}^{\infty} e^{-\frac{mu_z^2}{2kT}} du_z \iiint dx dy dz. \end{aligned}$$

Integrating the first three integrals on the right-hand side by equation 37, it reduces to

$$\frac{1}{g} \left( \frac{2\pi kT}{m} \right)^{\frac{3}{2}} \iiint dx dy dz.$$

The triple integral in the equation above is the total volume  $v$  occupied by all the molecules of the gas, since  $x, y, z$  extend over all the possible coördinates of position that a molecule might take on. Hence we find that the right side of the equation above further reduces to

$$\frac{v}{g} \left( \frac{2\pi kT}{m} \right)^{\frac{3}{2}}. \quad (364)$$

Thus equation 363 becomes

$$\sum_{n=1}^{n=i} e^{\frac{e_n'}{kT}} - e^{\frac{e_n''}{kT}} = \frac{v}{g} \left( \frac{2\pi kT}{m} \right)^{\frac{3}{2}} \iiint \dots \int e^{\frac{e_n''}{kT}} du_1 du_2 \dots ; dx_1 dx_2 \dots \quad (365)$$

Inserting equation 365 in 361, we have

$$a = -kNT \ln \left\{ \frac{v}{g} \left( \frac{2\pi kT}{m} \right)^{\frac{3}{2}} \right\} - kNT \ln \left\{ \iiint \dots \int e^{-\frac{e_n''}{kT}} du_1 du_2 \dots ; dx_1 dx_2 \right\}. \quad (366)$$

The second term on the right is not a function of the volume  $v$ , since  $x_1, x_2 \dots$  refer only to the coördinates of the internal degrees of freedom of a molecule measured with respect to a fixed point in that molecule. Consequently when we take the partial differential of equation 366 with respect to  $v$ , we have, according to equation 360,

$$p = - \left( \frac{\partial a}{\partial v} \right)_T = \frac{kNT}{v},$$

or

$$pv = kNT,$$

or

$$pv = RT,$$

where  $R$  is set equal to  $kN$ .

Equations 367 are recognized immediately as the familiar ideal gas law. Since  $v$  and  $N$  refer to 1 gram of the substance,  $R$  is obviously the gas constant per gram, and  $k$  the gas constant per molecule. As will be recalled,  $k$  appeared first as a constant of proportionality in equation 332, relating entropy with the probability of the state of the system. No other physical significance was, at that time, attached to it.

A relation connecting the specific heat at constant volume  $c_v$  with the specific heat at constant pressure  $c_p$  will now be developed. Recalling equation 51,

$$de = c_v dT,$$

and equation 49,

$$dq = de + p dv,$$

we have

$$dq = c_v dT + p dv. \quad (368)$$

Now, differentiating equation 367 and dividing the result by equation 368, we have

$$\frac{dp}{p} + \frac{dv}{v} = \frac{dT}{T}. \quad (369)$$

Solving equation 369 for  $p dv$  and substituting this into 368, we have

$$dq = c_v dT + p v \left( \frac{dT}{T} - \frac{dp}{p} \right).$$

Introducing  $R$  from equation 367, this becomes

$$dq = c_v dT + R dT - v dp.$$

If the pressure is kept constant,  $dp = 0$ ; and we have

$$dq = c_v dT + R dT.$$

Since the pressure is constant, this last equation becomes (by eq. 52)

$$c_p dT = c_v dT + R dT$$

or

$$c_p - c_v = R. \quad (370)$$

As equation 370 shows, there is always a constant difference between the specific heat of a gas at constant pressure and at constant volume; and this difference is the familiar gas constant per gram  $R$ .

# THE APPLICATION OF THERMODYNAMICS TO THE QUANTITATIVE DESCRIPTION OF THE STATE OF SOIL MOISTURE

## 60. Useful Concepts in the Interpretation of Soil-Moisture Phenomena

In some conceptions of the distribution of water in unsaturated soils, the water is thought of as spread over the soil-particle surface as films and water rings. Its behavior in the soil is accounted for solely on the basis that the water has surface tension, in virtue of which it distributes itself in a definite way throughout the soil, depending upon the shape of the pore space and upon the moisture content.

On the basis of this interplay of pore space, moisture content, and the surface-tension effects of water, explanations have been given for the experimental observations made in soil-moisture studies. Some apparent inconsistencies are revealed, however, by a review of the thermodynamic and hydrodynamic aspects of some of the studies made by vapor pressure, freezing point, dilatometer, centrifuge, and suction methods. By studying certain basic relations, we may uncover some of these difficulties.

The present equations in soil literature, relating vapor pressure over a water surface to the radius of curvature of that surface, are based on the assumption that the body of the liquid is outside the field of force exerted by the soil particles. This assumption is questionable at low moisture content, as is evident from the very fact that the presence of a field of force surrounding a solid surface must be assumed in explaining all capillary phenomena. Obviously, an attraction must exist between the solid material and the water in the region of the liquid-solid interface in order for the surface to be wetted and for the water to adhere to the solid surface; otherwise the vapor-water interface could not be concave to the vapor phase.

In addition, the literature shows that certain factors have not been included in dealing with the thermodynamics relating freezing-point depression of soil moisture to the free energy of the moisture. The treatment of the freezing-point depression of relatively moist soils has been partly taken up under case 3 of article 30; that of relatively dry soils, where the adsorptive force field comes into play, will be taken up in the following articles.

The latter treatment will incorporate the effect of the strong attractive forces exerted by the soil particles on the soil moisture in the region adjacent to the surfaces of the particles, as well as the osmotic effect of the solutes dissolved in the soil moisture. It will relate the freezing-point depression of soil moisture to its free energy and vapor pressure, with particular reference to measurements made by the dilatometer.

### 61. Need for Introducing the Concept of an Adsorptive Force Field in Dealing with Soil-Moisture Phenomena

The assumption of an adsorptive force in the region adjacent to the soil-particle surface is important in accounting for the behavior of moisture in soils. Without this assumption, the results observed are hard to explain, particularly for relatively dry soils. As was pointed out earlier, some of these difficulties become evident when we try to interpret the results of vapor-pressure studies. Further evidence for the necessity of introducing the concept of a force field surrounding the soil particle is furnished by studies of the freezing point of soil moisture.

*Adsorptive-Force-Field Indications from Vapor-Pressure Studies.*—Equation 271 indicates the relation between the soil moisture content and its associated vapor pressure if no adsorptive field is assumed. It is

$$\ln \frac{p}{p_0} = \frac{2\sigma \cdot v}{r \cdot RT} + (p - p_0) \frac{v}{RT} \quad (371)$$

and purports to determine the vapor pressure  $p$  immediately above a water surface whose radius of curvature  $r$  is given. All the other quantities in the equation are constants and can be obtained from a set of physical tables.

We are thus led to conclude that this equation should describe the relation between vapor pressure and moisture content in a soil, since  $r$  is a measure of moisture content. When  $r$  is large, the moisture content of the soil is high; when it is small, the moisture content is also small. Hence if we wish to find the behavior, more or less qualitatively, of the vapor pressure  $p$  with respect to moisture content at low moisture contents, we have merely to study the variation of the vapor pressure  $p$  in this equation with respect to the radius of curvature  $r$  of the air-water interface.

As mentioned above, however, this relation was developed by using an assumption that seems unjustifiable at low soil moisture contents. In developing equation 371 it was assumed that the soil particles do not attract the water molecules lying in the vapor-liquid interface and therefore do not affect their vapor pressure outside the interface. Curiously enough, we apparently cannot get interfaces concave towards the vapor phase without assuming that water adheres to the surface of the solid. Necessarily, therefore, the soil must have an adsorptive force field that attracts the water molecules. At low moisture contents this adsorptive field surrounding the soil particle must affect the vapor pressure and cause a deviation from equation 371. The vapor pressure of water in small capillaries has been found to be much smaller (145) than equation 371 would predict.

The idea of an adsorptive force field surrounding solid surfaces is not radical, since practically all explanations of adsorptive phenomena use some such concept. It involves the idea of a force being transmitted through space. Such forces are also called "field forces," "body forces," and "adhesive, attractive, or repulsive forces." Reference to some considerations and results bearing on this point is of interest. A consideration, for example, of the shape of the experimental curve (fig. 31) showing

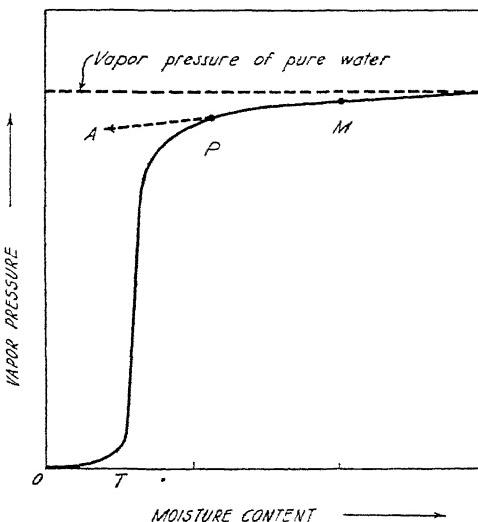


Fig. 31.—Vapor pressure of soil moisture as a function of moisture content.

the relation between vapor pressure and soil moisture content makes the introduction of the concept of an adsorptive field of force appear necessary.

If we postulate that the decrease of the vapor pressure of soil moisture, as the soil dries out, is caused entirely by the increase in the concentration of ionizable solutes in the soil solution, we should expect to have a greater slope of the curve between the moisture equivalent  $M$  and the permanent wilting percentage  $P$  than between the permanent wilting percentage  $P$  and the point  $T$ . In other words, for a given increase in concentration, we should expect a greater rate of decrease in vapor pressure at low concentrations (high soil moisture content) than at higher concentrations (lower soil moisture content), because the salt molecules are more dissociated at low concentrations. We should therefore expect the curve, as the soil is dried out, to continue in the direction  $A$ , whereas it actually turns sharply toward  $T$ . Some factors other than the presence of dis-

solved material seem therefore to come into play. One of these is the adsorptive force field surrounding the soil particle. It probably plays a minor role at the higher moisture contents. But this force becomes increasingly effective as the moisture content is decreased to the neighborhood of the permanent wilting percentage and increases very rapidly as the moisture content is further decreased.

We shall now point out the importance of the Maxwell distribution law at the lowermost soil moisture contents. The close approach of the curve (fig. 31) to the abscissa near  $T$ , at an appreciable moisture content, can be explained if we assume that this strong adsorptive field of force acts on the water molecules, inhibiting their outward movement into the vapor phase sufficiently to give a very small vapor pressure at appreciable soil moisture contents. That the curve does not actually strike the axis at  $T$  has been accounted for (art. 47 and 55) on the basis of the kinetic theory of matter, by the fact that molecules of the water film have widely different velocities. According to the Maxwell distribution law, some molecules move very rapidly, some move very slowly, but only the faster group can escape against the adsorptive force field. If all the molecules, on the other hand, had the same velocity, one would expect the vapor pressure to become zero at some appreciable moisture content  $T$ . At moisture contents below  $T$  none of the molecules would, on the basis of the latter assumption, have sufficient kinetic energy to pass beyond the adsorptive force field exerted by the soil particles; and we should have zero vapor pressure. Since, however, the water molecules have velocities as determined by the Maxwell distribution law, we may expect that no matter how strong the adsorptive field, some molecules will have energy enough to escape into the vapor phase and thus produce a small but appreciable vapor pressure.

The vapor-pressure curves reported by Edlefsen (46) and by Thomas (163) show this general trend, in that the vapor-pressure curves change their slope markedly at soil moisture contents where plants wilt; if the curve is extrapolated to zero vapor pressure, it intercepts the moisture-content axis at appreciable soil moisture contents. Apparently, therefore, the soil would have a zero vapor pressure at appreciable moisture contents if all molecules had the same speed. From his studies, Edlefsen concluded (42, 46) that adsorptive forces probably played an important role in soil moisture at moisture contents lower than the permanent wilting percentage.

In our considerations here, as in most soil-moisture literature, the state reached after prolonged drying of the soil at 110° C will be regarded as zero soil moisture content. As the temperature is raised to higher values, more water will of course be driven off; and, as pointed out by

Kelley, Jenny, and Brown (95), the steplike shape of their curves at extremely low moisture contents indicates that this moisture is chemically combined.

*Adsorptive-Force-Field Indications from Plant Behavior and Freezing-Point Data.*—As every student of soil moisture knows, the freezing point of soil moisture is less than 0° C; the amount of the depression increases as the moisture content decreases. Though the theoretical interpretation of such data will be given later, it is now pertinent to recall some qualitative facts that seem to require the concept of a field of force.

One cannot get sufficient concentrations of salts in soil moisture, having the ordinary proportions of nutrient elements for plant growth, to account alone for the observed freezing-point depressions of soil moisture at moisture contents in the vicinity of the permanent wilting percentage. In the first place, some of the nutrients will precipitate long before sufficient concentration can be reached to account alone for the observed freezing-point depression in the neighborhood of the permanent wilting percentage. By the time such a concentration is reached, the proportions of the nutrients will be seriously unbalanced. If this precipitation of necessary nutrients took place one might expect to find plants showing certain nutritional deficiencies in the neighborhood of the permanent wilting percentage. Such nutritional deficiencies are seldom if ever evident.

In the second place, the soil solution would be highly toxic to plants if the concentration of the soil solution were sufficiently high to account alone for the observed freezing-point depression in the neighborhood of the permanent wilting percentage. But it is a well-demonstrated fact that plants grow normally for all moisture contents above the permanent wilting percentage. As the transpiration rate over this range of moisture content is practically independent of moisture content, concentration of solute in the soil solution plays only a minor role in affecting the availability of soil moisture to plants.

And in the third place the freezing-point depression of soil moisture at the permanent wilting percentage is many times what it is at field capacity. To explain this enormous change in the freezing-point depression (as the moisture content is progressively decreased) on the basis of concentration of dissolved materials alone, one must assume that the concentration of solutes in the soil solution has increased many times more rapidly than the moisture content has decreased. This seems inconceivable, however, for apparently the concentrations should, to a first approximation, vary inversely as the moisture content.

Another phenomenon difficult to explain without the introduction of an adsorptive force field is that at the permanent wilting percentage the

rate of transpiration decreases abruptly. If the change in the difficulty of removing water from soil as the moisture content is decreased were caused entirely by dissolved materials, one would expect this difficulty to increase gradually as the moisture content becomes smaller. There should therefore be no sudden increase in the difficulty of removing water from the soil in the neighborhood of the permanent wilting percentage. As Edlefsen (42) has pointed out, this abrupt increase in the difficulty experienced by plants in obtaining water at the permanent wilting percentage indicates that as the moisture films get thin, other forces acting on soil moisture are brought into play. Apparently, therefore, we can explain this abrupt change by assuming that an adsorptive force field surrounds the soil particles and that the magnitude of this field increases very rapidly as the soil-particle surface is approached.

These notions agree with those of Parker (115) when he says:

At moisture contents below the water-holding capacity of the soil, the water is held to the soil by an attractive force commonly called adhesion. As the moisture content of the soil gradually decreases, the force with which the remaining water is held continually increases. This causes an increase in the freezing-point depression of the soil water, a decrease in the rate of evaporation and a decrease in the vapor pressure of the soil water as the moisture content is reduced. This force is great enough to prevent part of the soil water from being frozen at low temperatures.

Some, including Parker (114), believe that aside from dissolved material present, colloidal material produces a freezing-point depression not because it is in solution, but because it is surrounded by an adsorptive force field that compresses the capillary water films and that therefore increases the freezing-point depression.

Apparently, then, there are several reasons why the vapor-pressure depression, the freezing-point depression of soil moisture, and the behavior of plants in extracting soil moisture, cannot be explained on the basis of dissolved materials alone and thus why it seems necessary to introduce the idea of an adsorptive force field surrounding the soil particles, which in turn, creates a hydrostatic pressure in the soil solution.

#### 62. The Use of the Free-Energy Concept in Interpreting Soil-Moisture Phenomena

In past quantitative studies of the energy relations of a soil-moisture system, a mathematical function known as "capillary potential," "total potential," or merely "potential" has been used (20, 30, 45, 46, 55, 57, 58, 59, 81, 91, 103, 104, 111, 125, 126, 138, 153, 154, 159). The total potential of soil moisture has been defined as  $\Phi = \psi + \omega + \lambda$ . Here  $\psi$  is the capillary, or pressure, potential, existing because the water is under a tension or pressure;  $\omega$  is the gravitational potential, as used in the past, but may include all potentials that exist by virtue of an adsorptive force

field acting on soil moisture (for example, the adsorptive field exerted by soil particles on moisture); and  $\lambda$  represents the osmotic potential that the moisture has by virtue of the material dissolved in it. The idea of potentials has also long been used in the study of electricity, magnetism, and mechanics. In thermodynamics and physical chemistry, an analogous function called "free energy" or "thermodynamic potential" has been introduced.

Just as one must, considering a gravitational field, refer the potential to some datum, often taken at sea level, so in dealing with soil-moisture energy relations one must also choose some datum, or reference point. This datum, for soil-moisture energy, was usually taken as free, pure water. Capillary potential, often called "pressure potential," is therefore defined by different investigators as the work done, per unit mass of water, against the capillary field forces in moving water from the free, pure water, the datum, to the point where the potential is to be evaluated.

Capillary potential as thus defined is a mechanical potential measuring the energy of compression or tension in the water. Gravitational as well as osmotic potentials are defined similarly, the free, pure water surface being always used as the datum of potential. Students of soil moisture have usually been interested only in the liquid state of water. They have defined the potential of soil moisture in such a way that its magnitude is calculated with respect to a datum at the same temperature. In other words, they have considered the soil moisture and the free, pure water (used as the datum) to be at the same temperature. In the past, they have not inquired whether or not the potential of the reference point changed with temperature.

As pointed out (art. 21), when one must consider all three phases of water existing in equilibrium with each other, together with the effects of adsorptive force fields and temperature on the energy relations of soil moisture, one may conveniently introduce a more comprehensive thermodynamic function called "free energy." This function, as already mentioned, has had its most extensive use in the field of physical chemistry, where the investigator is interested in all phases of a substance rather than in the liquid phase only. This quantity  $f$ , free energy, is defined according to article 21 by the equation

$$f = h - Ts, \quad (372)$$

where  $h$  represents the heat content,  $T$  the absolute temperature, and  $s$  the entropy of the system. At this point we are interested mainly in the characteristics of the function  $f$ . This, as well as the other terms appearing in equation 372, has been more completely discussed in previous

articles. As is usually pointed out in texts on thermodynamics, a change in free energy  $\Delta f$  of a system from one value to another represents the maximum useful work obtainable from the given process when it occurs at a constant temperature and pressure. Curiously enough, almost all the major changes in soil moisture take place under the conditions of constant temperature and pressure. This function seems, therefore, peculiarly adapted to soil-moisture studies. Free energy, because of the more generalized meaning given to it, is a more appropriate function for our purpose than is potential.

At this point we may well discuss certain characteristics of this function which are a consequence of the facts outlined in articles 21, 22, and 39 and which will be used in describing the energy states and energy changes of soil moisture. Where we speak of a change in free energy without any qualification, we assume that the process is carried out isothermally.

1. The absolute, or total, value of free energy as defined above cannot be measured. We must content ourselves with measuring changes in the function, just as in the case of the gravitational potential, where we always measure not the absolute value but rather its difference measured with respect to some datum, usually taken as sea level (art. 39).

2. When a substance exists in several different states in equilibrium with each other, the specific free energy of that substance is the same in all of the states (art. 22). For example, when water in a salt solution is in equilibrium with its vapor and ice, the specific free energy is the same in all three states—ice, water, and vapor.

3. The change of free energy in any transformation of a system in going from a state *A* to a state *B* equals (eq. 101) the mechanical work required to go from *A* to *B* at constant temperature, neglecting the work of expansion against constant pressure.

4. The increase in the total free energy of a system, where the surface area of the air-water interface is increased by an amount equal to  $dA$ , is equal to  $\sigma dA$ , where  $\sigma$  equals the surface tension of water (eq. 208).

5. The increase in free energy of a system containing  $v$  cubic centimeters of water, where the pressure on the water is changed from  $P_1$  to  $P_2$ , equals  $v(P_2 - P_1) = v \Delta P$  (eq. 156). This relation is the same as used by soil-moisture investigators to express changes in pressure or capillary potential  $\psi$  caused by changes in hydrostatic pressure.

6. The difference in specific free energy between vapor at a pressure  $p_2$  and at  $p_1$  (eq. 236) is  $\Delta f = f_2 - f_1 = RT \ln \frac{p_2}{p_1}$ , where  $R$  equals the gas constant per gram and  $T$  equals the temperature of the vapor. A measure of the maximum capacity of the system for performing useful work is  $-\Delta f$ . This equation expressing changes of free energy in terms of changes in

vapor pressure of a liquid is identical with equations used by soil-moisture investigators for expressing the potential of water as a function of vapor pressure (20, 46, 104, 139, 154).

7. The thermodynamic relations are available for determining the dependence of free energy on temperature. These have been discussed in articles 21 and 23, and their application to soil moisture will be further considered in articles 72 to 81. The potentials as previously defined in soils did not lend themselves to such a determination, since the equations did not contain the temperature explicitly. The temperature was, of course, involved implicitly; but the mere knowledge of the potential at one temperature did not enable one to calculate it at some other temperature. In other words, it had to be determined by experiment at each temperature. Clearly, free energy defined by equation 372 as  $f = h - Ts$  contains the temperature explicitly.

The choice of terms in this connection is not easy. "Free energy" would appear to be a more appropriate term than "potential" when one is dealing with systems that contain all three of the phases. The word is equivalent, furthermore, to "potential" as applied previously in the soil literature that deals with the liquid phase. For these reasons it has been adopted here. The term "molal free energy" appears often in the literature of physical chemistry. In the present discussion, however, we are not especially concerned with the molal free energy of water; rather, we are interested in the change in free energy per unit mass, or in the specific free energy. For the sake of brevity, however, we shall use the general term "free energy," with the understanding that it refers to the free energy per unit mass.

The specific quantities of a substance are obtained immediately from the molal by merely dividing the latter by the molecular weight of the substance. Obviously, according to the discussion above, the total potential, as used previously in literature on soil moisture, and the specific free energy, as here defined, are somewhat analogous functions both dimensionally and quantitatively except for the more generalized meaning associated with the latter. Since, as pointed out before, the total potential equals the sum of the osmotic pressure and the adsorptive-force-field potentials, then the specific free energy of the substance in any state also equals the sum of the osmotic pressure and the adsorptive-force-field potentials in the liquid state.

Other factors may contribute to the total free energy of the soil moisture. For example, the presence of the water molecule in the adsorptive-force field surrounding the soil particles may give rise to an orientation of the molecules. This orientation is one form of potential energy that the water may possess.

63. The Role of the Adsorptive-Force-Field Concept in the Interpretation  
of Soil-Moisture Properties

To illustrate the usefulness of the function called "free energy" when applied to the description of the energy relations existing in soil moisture, and to show its relation to the other potentials found in the literature and just previously described, let us consider the system *A* shown in figure 32,

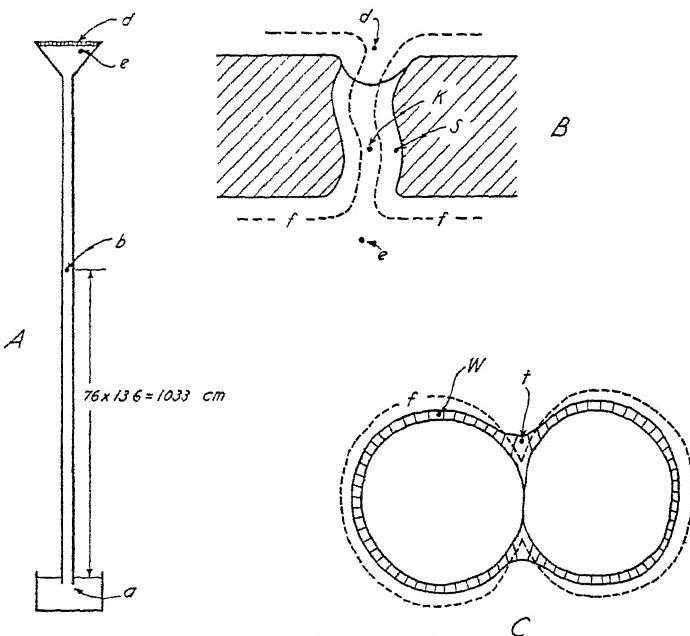


Fig. 32.—Hypothetical effect of an adsorptive force field.

consisting of a glass tube sealed at the top to the open end of an inverted porous vessel, here in the shape of a cone. The system is filled with pure water, the lower end of the tube being placed in the vessel at point *a*; and the entire system is exposed to atmospheric pressure. At point *a* we have free, pure water, which we shall use as our datum both for gravitational potential and for pressure potential. Assuming that we have pure water, the osmotic potential is zero throughout. It should be recalled that the total specific free energy equals the sum of all the potentials. When water in this system is in equilibrium, the specific free energy is the same throughout; and therefore no energy will be required to move water from *a* to any other point in the liquid. This follows from the second and third characteristics of free energy (art. 62).

The sum of the pressure, or capillary, potential and the gravitational potential is constant and equal to zero for all points in the liquid since the

total potential is zero at point *a*. At any point, therefore, the capillary potential and the gravitational potential are equal in magnitude but opposite in sign. At the point *b*, for example,  $76 \times 13.6 = 1,033$  centimeters above *a*, the gravitational potential will have increased by an amount 1,033 gram-centimeters per gram, whereas the capillary or pressure potential will have decreased by the same amount, leaving the total potential or free energy unchanged. At a point to the right or left of *b*, for example, the water has a hydrostatic pressure of  $-1,033$  grams per square centimeter with respect to point *a* except when it is close to the wall of the glass tube, where adsorptive forces become effective. These forces will now be discussed.

Consider in detail a pore (fig. 32, *B*) in the porous material at *d* of figure 32, *A*. Water at the point *k* in the center of the pore might actually be under tension, whereas water at *s* near the wall of the pore might be under compression because of an adsorptive force field surrounding the clay surface whose range of influence reaches out as far as the dotted lines *f*. Clearly, therefore, water under tension might be in equilibrium with water under pressure; that is, the water might have the same total potential or the same specific free energy throughout, although the partial potentials vary considerably under the widely different conditions of pressure and position found in the water mass.

Figure 32, *C*, shows a hypothetical picture of two soil particles surrounded by a film of water, held on by an adsorptive force field extending out from the particle as far as the dotted line *f*. The cross-hatched area represents the film of water. At a point *t* the water is under a negatively curved surface and might therefore be expected to be under a tension, whereas the water at *w* is under a positively curved surface as well as inside the adsorptive force field. Both these effects would tend to produce a positive pressure at *w*. Here, again, we have an example, comparing points *t* and *w*, of an equilibrium condition where water under pressure is in equilibrium with water under tension, since we know that water actually distributes itself approximately as shown in the figure when two soil particles are brought into contact and that there is no tendency for any preferential movement of the water when the equilibrium distribution of soil moisture has been established.

The fact that in the same mass of soil moisture, one region may be in a state of tension and another under great compression, although the whole mass of soil moisture is at equilibrium, is rather important in our interpretation of the so-called "capillary-potential measurements" frequently made on soil moisture. The capillary potential is usually determined by placing in the soil a porous clay bulb, filled with water and connected to a mercury manometer. The water in the manometer is adjusted until the

water in the porous bulb is in equilibrium with the soil moisture. That is, the water in the bulb and manometer is in such a state of tension that it balances the pull exerted by the moisture in the soil.

On the basis of such evidence, seeming to indicate a state of tension throughout the soil moisture, attempts are made to explain such properties of soil moisture as the variation of vapor-pressure depression with decrease in moisture content as well as the distribution of moisture within the soil, it being assumed that the water is held in the form of water wedges at the points of contact of soil particles.

Actually, even though the water in the manometer and bulb is in a state of tension, much of the water in the soil is probably far from being so, except at relatively high moisture contents. If a moisture film is acted upon by an adsorptive force field, it might be expected to be under positive hydrostatic pressure. If so, it can be in equilibrium with a body of pure water only if the latter is placed in the proper state of tension. This follows because an adsorptive force field reduces the escaping tendency of the water molecules of the soil moisture. This reduces the vapor pressure and consequently gives the soil moisture a negative value of free energy. For a body of pure water to be in equilibrium with the soil moisture, its free energy must also be lowered to the same negative value (art. 22). This can be accomplished by placing it under tension.

To attain vapor pressure and free energy corresponding to soil moisture at the permanent wilting percentage, the soil moisture would have to be under a tension of approximately 16 atmospheres. According to a well-known fact, only with special experimental precautions can water be made to withstand tensions much greater than 1 atmosphere, and this only after most of the dissolved air has been carefully removed. At the lower moisture contents, therefore, tension is unlikely to be an important contributing factor to the value of the free energy of soil moisture.

If free, pure water is to be in equilibrium with soil moisture, it must be placed under tension. This fact indicates that the moisture adjacent to the soil particle must be under the influence of an adsorptive force exerted by the soil particles. Otherwise, the soil moisture will not adhere to the soil particles when a tension exists at some other point in the soil moisture.

If an attractive force is exerted by the soil particles on the soil moisture, it must act through a finite distance. Thus a positive hydrostatic pressure is produced. Consequently, the water molecules contained within a layer adjacent to the soil-particle surface will be attracted towards the surface. The molecules farthest away will be attracted and will press on the adjacent ones closer to the soil surface, which will, in turn, press on those still closer to the soil-particle surface. Thus a hydrostatic pressure

is built up in the layer adjacent to the soil-particle surface, increasing as the soil surface is approached. A rough analogy is found in the increase of hydrostatic pressure in a reservoir of water as one descends towards the bottom. In both cases an adsorptive force field acts on the water producing the pressure. In the former case, the force is probably electrical; in the latter, gravitational.

Thus, judging from the factors that determine equilibrium of soil moisture and from the properties of the thermodynamic function called "free energy," an appreciable amount of the soil moisture is not under tension even at the high moisture contents. Rather, it is under an adsorptive force field surrounding the soil particle, which entails a hydrostatic pressure increasing as the surface of the soil particle is approached. Dissolved material, which doubtlessly increases in concentration as the surface of the soil particles is approached, further augments the effects produced by the adsorptive field. At higher moisture contents, some of the soil moisture is under tension because of the negative curvature of the air-water interface, and the effect of this might well be, according to case 3 of article 30, to lower the freezing point of the soil moisture. This freezing-point depression would be in addition to that caused by osmotic pressure.

Let us now consider briefly the effects of the positive hydrostatic pressure on the freezing point of soil moisture in the vicinity of the soil-particle surface. Also, we shall assume that the ice separating out, as more and more of the soil moisture is frozen, continues to be attracted towards the soil-particle surface, in contrast to what was considered under case 3 of article 30.

To learn how pressure and tension affect the freezing point of soil moisture, we may refer, first, to Le Châtelier's theorem which states that when any isolated system is acted upon by an influence, a change will occur within the system, making the effect of the influence less than if the change had not occurred.

To understand the consequence of this theorem when applied to the problem of the change in freezing point of soil moisture, consider a system composed of pure water and ice at  $0^{\circ}\text{C}$  in a closed system. According to the theorem, if pressure is applied to this system, the volume will decrease and will thereby tend to relieve the applied pressure. Obviously, the only way this can occur is for ice to melt, since the volume of water is less than the volume of ice. Conversely, if a tension is applied to the water (that is, if the pressure is decreased) a volume change will occur that will tend to relieve the tension. This, obviously, can happen only if the volume increases, which means that some of the water will change to ice. Clearly, therefore, pressure decreases the freezing point of water, whereas tension tends to increase it.

Le Châtelier's theorem is useful in reasoning qualitatively on various phenomena. It does not, however, enable us to get quantitative results. For this purpose, as applied to the problem at hand, we must resort to the thermodynamic relation known as the Clausius-Clapeyron equation (eq. 186). This will be recognized as case 1 of article 30.

A consideration of this equation, when applied to such a system as that above, leads one to inquire why, if soil moisture is under tension, we do not observe a freezing point in it higher than 0° C. The Clausius-Clapeyron equation is

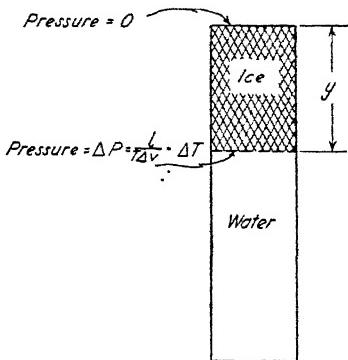
$$\frac{\Delta P}{\Delta T} = \frac{l}{T\Delta v}.$$

Here  $\Delta v$  equals the volume contraction of ice per unit mass upon melting;  $l$  is the heat absorbed by ice upon melting and is really a positive quantity in this particular case since heat is actually absorbed when ice melts; and  $T$  is the absolute temperature at which the transformation occurs. Thus, if we place water under tension,  $\Delta P$  is negative. The right-hand member of the equation is already negative because  $l$  is of opposite sign from  $\Delta v$ . Hence  $\Delta T$  must be positive. By placing water under tension we are therefore led to the conclusion that we raise its freezing point.

So far as we are aware, no one has ever observed the freezing point of soil moisture to be higher than 0° C. And yet, as mentioned before, water in soils is sometimes thought to be in a state of tension. There are three reasons why we probably do not observe any elevation of the freezing point above 0° C as would be predicted from our previous considerations. First, the Clausius-Clapeyron equation shows that the freezing point changes very slowly with changes in pressure; one could probably never get water in soils under sufficient tension to raise its freezing point a measurable amount, since (according to the Clausius-Clapeyron equation) a tension of 133 atmospheres is required to increase the freezing point 1 degree. Second, there are always salts present that tend to depress the freezing point in soils. Third, when the water content of the soil has been reduced until the water should actually be under an appreciable tension, due to film curvature according to article 42, the water films are thin enough so that they are probably under the influence of an adsorptive force field exerted by the soil particles themselves, which tends to compress the water and thus lower its freezing point.

To show more clearly how the adsorptive force surrounding the soil particles affects the properties of soil moisture, let us consider an analogous situation more familiar than that found in soils. Consider an adsorptive force field acting on pure water. If we have a column of water in a vertical position on the earth's surface, every particle of water through-

out will be acted upon by the earth's gravitational field, and a definite pressure will be produced at the bottom of the column. If the height is doubled, the hydrostatic pressure will be doubled. Also, measurement of the hydrostatic pressure at different distances below the upper surface of the water will show that the pressure increases at a constant rate with respect to changes in height. Obviously, neither this doubling of the hydrostatic pressure by doubling the height of the column, nor the uniformity in the rate of increase of pressure as one descends in the column, would hold true if the length of the column were of the same order of



*Temperature of column =  $\Delta T$ ° below 0°C*

Fig. 33.—Position of water-ice interface at depth  $y$  below the surface when the column is subjected to  $\Delta T$  degrees below 0°C.

magnitude as the radius of the earth, since the gravitational field of force is known to obey the inverse square law. In other words, the weight of unit mass of water varies inversely as the square of its distance from the center of the earth. If, therefore, we were dealing with a water column of a height comparable with the radius of the earth, we should find a significant increase in the weight (gravitational constant) of unit mass of water as we descend in the column. Thus hydrostatic pressure, in such a case, is not proportional to the depth below the free water surface, but instead increases much more rapidly as determined according to Newton's inverse-square law. On the other hand, in a reservoir whose depth is small as compared with the earth's radius, the weight of a unit mass of water at the top and bottom is practically the same, and consequently the hydrostatic pressure is nearly proportional to the depth.

Let us now consider how freezing temperatures affect this column of water. If we choose some hydrostatic pressure  $\Delta P$  corresponding to that at some depth  $y$  of figure 33 in the column and if we lower the entire

column to a temperature  $\Delta T$  degrees below  $0^\circ \text{ C}$  such that  $\Delta P$  and  $\Delta T$  are related by the Clausius-Clapeyron equation,

$$\frac{\Delta P}{\Delta T} = \frac{l}{T\Delta v},$$

all the water above the depth  $y$  will be frozen; that below, unfrozen. The temperature of the column  $\Delta T$  degrees below  $0^\circ \text{ C}$ , and the hydrostatic pressure  $\Delta P$  at the water-ice interface will always be related according to the equation above. Thus the thickness of the ice on a pond would depend only on the temperature if there were no convection and if sufficient time and heat were available to establish equilibrium conditions.

#### **64. Effect of an Adsorptive Force Field Surrounding Soil Particles on the Freezing Point of Soil Moisture**

The situation described above, relating the adsorptive force acting on the soil moisture to its freezing-point depression and to the amount of water frozen out, seems analogous to that found in the soil-moisture film surrounding and immediately adjacent to a soil particle, the additive effect of surface tension and osmotic pressure being neglected for the present.

Since the postulated fields of force are assumed by various investigators to be anywhere from the inverse-square law to an inverse fifth law, clearly the force of attraction on a particle of water increases very rapidly as it approaches the soil-particle surface. The hydrostatic pressure in water, therefore, increases very rapidly as the surface of a soil particle is approached. As was mentioned earlier, a measurement of the hydrostatic pressure enables one to calculate easily the partial free energy due to hydrostatic pressure, since the latter is numerically equal to the hydrostatic pressure in the c.g.s. system. This follows according to equation 156 because the free energy

$$\Delta f = \frac{\Delta P}{\rho} = v \Delta P_P$$

where  $\rho$  and  $v$  are the density and specific volume of water respectively, and where each is approximately equal to unity. Here  $\Delta P_P$  represents the hydrostatic pressure.

Now consider figure 34, *B*, which consists of a layer of soil covered with a layer of pure water over which is a layer of ice, both the ice and the water being acted upon by an attractive force that increases in magnitude very rapidly as one approaches the soil-particle surface. The figure represents a small radial section through the soil particle; since we are

considering only a small element of soil-water interface, it can be represented by a straight line. (The following considerations would not be altered if the section of the surface were curved.) Figure 34, A, drawn to the same scale as 34, B, represents the trend, within the water and ice layers, of the hydrostatic pressure resulting from the adsorptive forces exerted by the soil particle.

The water-ice interface is the locus of points where the two phases, ice and water, are at equilibrium under the existing temperature and hydrostatic pressure. Points above this locus have too low a pressure for

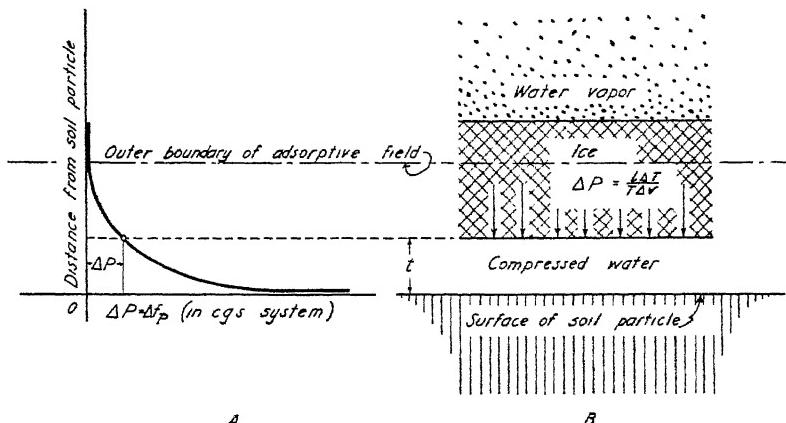


Fig. 34.—Relation of the adsorptive force field to the amount of frozen and unfrozen water in soils at a given temperature below zero where  $\Delta f_p$  is the partial free energy due to pressure;  $l$  is the thickness of the unfrozen layer of water;  $l$  is the specific heat of fusion;  $\Delta v$  is the change in specific volume when water freezes;  $T$  is the temperature of soil moisture;  $\Delta T$  is the number of degrees below  $0^\circ\text{C}$ , of the soil moisture; and  $\Delta P$  is the hydrostatic pressure at the water-ice interface by virtue of the soil adsorptive force field.

water to exist at the given temperature, whereas points below have too high a pressure for ice to exist. At the interface, therefore, the hydrostatic pressure must be  $\Delta P$  (as determined by the Clausius-Clapeyron equation) if the whole system is subjected to a temperature  $\Delta T$  degrees below  $0^\circ\text{C}$ , since both phases are in equilibrium at the interface.

In every respect, the present case of a partially frozen soil-moisture film is analogous to the case of a partially frozen reservoir of water considered in the previous article. By means of the Clausius-Clapeyron equation of article 27 or of case 1 in article 30, the pressure and therefore the free energy at the water-ice interface can be calculated for any freezing-point depression  $\Delta T$  degrees. Here, of course, we are dealing only with the contribution of the hydrostatic pressure to the free energy of soil mois-

ture. The hydrostatic pressure, in this case, exists because of the field or adsorptive forces that the soil particles exert on the water.

Measurements of the amount of unfrozen water remaining at different freezing-point depressions, where different amounts of ice are frozen out, together with a knowledge of the total area of the water-soil interface, would furnish sufficient information to construct the curve shown in figure 34, A, showing how the free energy due to hydrostatic pressure in the soil moisture at a given point is related to the distance of that point from the soil surface. The amount of unfrozen water divided by the area of the interface gives the average thickness of the film of unfrozen water.

In constructing such a curve, one should remember that the total free energy, which is the same throughout the soil moisture, is equal at any given point to the sum of the partial free energy due to hydrostatic pressure and that due to the adsorptive force field at that point. The total free energy may also be obtained (eq. 236) from such measurements as vapor pressure. The partial free energy due to the field is found, therefore, immediately from the difference between the total free energy and the partial free energy due to hydrostatic pressure. It is the gradient of this partial free energy, due to the adsorptive field at any point, which gives the magnitude of the force exerted by the soil on a water particle located at that point.

Clearly, then, the presence of an adsorptive force surrounding the soil particles increases the magnitude of the component of the free energy due to hydrostatic pressure as well as the freezing-point depression of soil moisture.

This effect of the adsorptive force field in producing hydrostatic pressure and therefore changing the free energy of the soil moisture is distinct from, and should not be confused with, the change in the free energy of the soil moisture caused by the mere presence of the soil moisture in the adsorptive force field surrounding the soil particle (art. 26). In the presence of an adsorptive force field, the partial free energy of the moisture (due to the position of the moisture in the field) decreases as the partial free energy (due to the hydrostatic pressure caused by the field) increases. A detailed consideration of these relations is taken up in article 69.

#### 65. Effect of Dissolved Material and Hydrostatic Pressure on the Freezing Point and the Free Energy of Soil Moisture

Considerations of the effect of dissolved material and hydrostatic pressure on the freezing point and the free energy apply especially to soil moisture in the vicinity of the soil-particle surface. Let us first consider how dissolved material contributes to the freezing-point depression of soil moisture. This effect of dissolved material is superimposed upon the

effect of the adsorptive force field discussed in the previous article. The condition we wish to discuss is represented in figure 35 as part of a radial section of a soil particle covered by a layer of soil solution over which is a layer of pure ice. As the temperature is lowered, the water-ice interface moves in toward the soil solution, concentrating it. The free energy of the water just inside the water-ice interface, expressed in terms of the osmotic pressure  $\Delta P_o$ , can be calculated by the well-known equation 148

$$\Delta f = -v\Delta P_o.$$

According to equation 187, an increase in the hydrostatic pressure, as

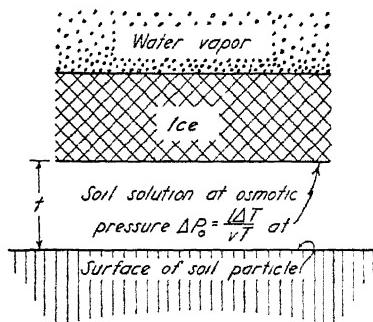


Fig. 35.—Part of a radial section through a soil particle covered by a layer of soil solution over which is a layer of pure ice; here  $t$  is the thickness of the unfrozen layer of water containing dissolved salt;  $l$  is the latent heat of fusion;  $v$  is the specific volume of water;  $T$  is the temperature of soil moisture;  $\Delta T$  is the number of degrees the whole system is below  $0^\circ \text{C}$ ;  $\Delta f_o$  is the free energy due to osmotic pressure of soil solution at the liquid-ice interface; and  $\Delta P_o$  is the osmotic pressure of the soil solution at the liquid-ice interface. Since  $\Delta f_o = -v\Delta P_o = -\Delta P_o$  and  $v = 1$  in the c. g. s. system, we have

$$\Delta f_o = -\Delta P_o = \frac{l\Delta T}{vT},$$

according to article 29.

well as an increase in the osmotic pressure or salt concentration (eq. 200), lowers the freezing point of water. Since both these factors are present in soil moisture in the vicinity of the soil-particle surface, the total freezing-point depression is the sum of the depressions produced by each factor separately. Stated quantitatively,

$$\Delta T = \Delta T_P + \Delta T_O. \quad (373)$$

Here  $\Delta T_P$  represents the depression of the freezing point due to hydrostatic pressure,  $\Delta T_O$  represents the freezing-point depression due to dissolved material, and  $\Delta T$  represents the total observed depression. But

increases in hydrostatic pressure cause increases in free energy (eq. 156), whereas increases in concentration of dissolved material cause decreases in free energy of the water (eq. 151 and 222). These facts will be amplified in the following discussion.

As shown in article 25, the  $\Delta f_P$  due to the presence of hydrostatic pressure is given by  $\Delta f_P = v \Delta P_P$ , where the subscript  $P$  connotes hydrostatic pressure. Also, according to article 24,  $\Delta f_O$  due to the presence of dissolved material causing the osmotic pressure  $\Delta P_O$  is given by  $\Delta f_O = -v \Delta P_O$ , where the subscript connotes osmotic pressure. Clearly, therefore, the total change in free energy  $\Delta f$  due to combined changes in concentration of dissolved material, as well as hydrostatic pressure, is given by the equation

$$\Delta f = \Delta f_P + \Delta f_O = v \Delta P_P - v \Delta P_O. \quad (374)$$

Experimentally it is often hard to measure  $\Delta P_P$  and  $\Delta P_O$ . It is therefore convenient to substitute, for these terms, quantities more easily determined experimentally. We can do this by referring to equation 187, from which we see that

$$\Delta P_P = \frac{l \Delta T_P}{T \Delta v}.$$

Here, it will be recalled,  $\Delta v$  is always negative, since ice contracts upon melting. By referring to equation 200, we see that

$$\Delta P_O = -\frac{l \Delta T_O}{T v}.$$

Substituting these in equation 374, we have

$$\Delta f = \frac{v l \Delta T_P}{T \Delta v} + \frac{l \Delta T_O}{T}. \quad (375)$$

Here  $\Delta f$  has been expressed in terms of  $\Delta T_P$  and  $\Delta T_O$  and other quantities that can be obtained from any table of physical constants. The first term on the right of equation 375 is inherently positive when the hydrostatic pressure is increased, since both the freezing-point change  $\Delta T_P$  and the change of volume  $\Delta v$  are negative. The second term, on the other hand, is inherently negative, since the change in the freezing point  $\Delta T_O$  of the solution is negative when soluble material is added. Thus the two terms on the right of equation 375 are of opposite sign.

*It is sometimes thought that because both positive hydrostatic pressure and*

dissolved material decrease the freezing point of a solution, these two factors should be additive in producing changes in the total specific free energy of the solution. As can be seen from both equations 374 and 375, however, this is not the case, since the changes in the free energy produced by hydrostatic pressure and osmotic pressure are of opposite sign.

Thus, for example, the concentration and hydrostatic pressure in the soil solution might be such that  $\Delta T_P$  and  $\Delta T_O$  would be so related that the total change in specific free energy  $\Delta f$  in equation 375 would be zero. In this case, the partial specific free energies produced by hydrostatic pressure and dissolved material are equal in magnitude but of opposite sign.

Clearly, then, one of the most important problems related to the analysis of freezing-point data on soils involves the separation of the observed freezing-point depression into its two components—namely, that due to dissolved material and that due to hydrostatic pressure.

The free energy of moist soil is then the sum of the free energies due to osmotic pressure and hydrostatic pressure, as well as the free energy due to the presence of the water in the adsorptive force field surrounding the soil particle. The latter has been considered in detail (art. 26) and will be considered later (art. 68 and 69). Only the former two factors would be expected to produce a freezing-point depression of soil moisture.

A quantitative thermodynamic treatment will be given in article 69 incorporating the factors mentioned above, for determining the free energy of soil moisture from measurements made with the dilatometer.

#### 66. Methods of Making Freezing-Point Measurements on Soils

Two methods are commonly used in making cryoscopical measurements on soils or other materials. In one (often called the Beckmann technique, since the procedure followed is largely that used by Beckmann in determining the freezing points of solutions) the soil sample is prepared at a certain moisture content and is placed in a vessel in which is inserted a sensitive thermometer or other temperature-measuring device. Then the temperature of the moist sample of soil is lowered until freezing of the moist soil is just initiated. This temperature is then noted. A series of such measurements of the freezing point made on several separate soil samples, each at a different moisture content, furnishes the data necessary to construct a curve showing the dependence of the freezing point of soil moisture on the soil moisture content.

In the other (often called the dilatometer method) whose thermodynamic treatment will be taken up in article 69, the sample of soil to be studied is placed in a closed vessel on top of which is attached a long vertical capillary tube. More than enough water is added to saturate the

soil, the amount of which is carefully determined. On top of the saturated soil is added some light oil (for example, kerosene) to fill completely all remaining space in the vessel, as well as a small part of the lower end of the capillary tube. The temperature of the vessel and of its contents is lowered until ice is formed within the saturated soil. A change from water to ice causes the contents of the vessel to expand. This expansion, due to the formation of ice, forces the oil up the capillary tube, which is calibrated so that the exact amount of expansion can be calculated and therefore the amount of water changed to ice. Knowing the amount of ice formed, one can calculate the amount of water remaining unfrozen, since the total amount of water in the soil is known. Thus by determining the amount of unfrozen moisture in the more-than-saturated soil sample, for a series of temperatures below 0° C, we can, as with the Beckmann method, plot a curve showing the dependence of the amount of unfrozen moisture in the soil on the corresponding soil temperature. In contrast to the Beckmann method, we here obtain the entire curve from but one soil sample.

#### 67. Previous Quantitative Interpretation of Freezing-Point Data

Data are available on the freezing point of moist soils (23, 24, 52, 77, 114). Some authors have made no attempt to interpret their findings in terms of thermodynamic equations. Although certain others have considered this aspect of the problem, further analysis appears necessary.

The effects of hydrostatic and osmotic pressure of the solution on the depression of the freezing point have been discussed earlier. In analyzing freezing-point data, no one seems to have made any quantitative use of the hydrostatic pressure caused by the presence of an adsorptive field surrounding soil particles, although Bouyoucos (23) considered it qualitatively and concluded that it did not play a role in what he called "free water." Bouyoucos' work on the freezing point of soil solutions seems to indicate that he was convinced that the freezing point was largely determined by the concentration of dissolved material; for he said, "All evidences, both direct and indirect, point overwhelmingly to the fact that these high depressions of the freezing point are produced by, and represent actual concentrations." He apparently had certain doubts, nevertheless, for he made the following statement: "The foregoing hypothesis, however, does not explain why the lowering of the freezing point increases in a geometric progression while the moisture content decreases in an arithmetical progression, and [does] not follow a direct inverse proportionality ratio (approximately) as might be expected." As if he felt called upon to introduce another hypothesis, he remarked, "The hypothesis is also offered that some of the water contained by the soil

might be either loosely chemically combined or physically adsorbed, or both . . .”

Schofield (138) interprets the freezing-point data secured with the Beckmann method on unsaturated soils by means of an equation, presumably meant to be equivalent to equation 200, giving the relation between the freezing-point depression and the osmotic pressure of the soil moisture. Although he does not specifically make the statement, we may logically conclude, in view of this similarity in the equations after suspected typographical errors are corrected, that he attributed the depression of the freezing point of soil solution entirely to dissolved material. On the other hand, since his expression is similar to equation 205 obtained under case 3 of the generalized Clausius-Clapeyron equation, it may be that he assumed the water, at the water-ice interface, to be under a different pressure from that in the ice. That is, as the water under tension freezes out, it separates out to the higher pressure of one atmosphere. This inequality of hydrostatic pressures at the water-ice interface, when the soil moisture is under tension, seems plausible, but more experimental work is necessary to substantiate it.

A quantitative interpretation of the behavior of the freezing-point depression of saturated soils is given in articles 64, 65, and 69.

#### 68. Effect of an Adsorptive Force Field on the Freezing Point of Soil Moisture as Measured by the Beckmann Method

When the freezing point of soil moisture is being determined by the Beckmann technique, the soil might be far from saturated, and very little if any of the water would then be expected to be under tension, so that case 3 of article 29 probably does not apply. In consequence, the adsorptive force field surrounding the soil particle will extend beyond the vapor-liquid interface of the moisture films. Figure 36, A, represents a radial section through the water-soil interface. The adsorptive force field is assumed to extend out to the dotted line F. Figure 36, B, shows a similar section through a body of free water unaffected by any soil particle or other extraneous force field except that due to the body of water.

Consider the surface layer of water of thickness  $\Delta t_1$ , which is part of the whole water film of thickness  $t_1$  on the soil particle. Let us inquire how the average hydrostatic pressure in  $\Delta t_1$  compares with that in a similar layer  $\Delta t_2$  on free water, and how this difference in hydrostatic pressure influences their respective freezing points. If the average hydrostatic pressure in  $\Delta t_1$  is greater than in  $\Delta t_2$ , the freezing point of  $\Delta t_1$  should be expected to be the lower, according to the Clausius-Clapeyron equation, 187. It will be noticed that we are assuming that the hydrostatic pressure at the liquid-ice interface is the same in both phases and that, there-

fore, the type of freezing considered by case 1 of article 30 applies. Since  $\Delta t_1$  is within the sphere of influence of the adsorptive force field surrounding the soil particle, its hydrostatic pressure will be greater and will increase progressively as the surface of the soil particle is approached (art. 63) and thus will have a finite freezing-point depression by virtue of the hydrostatic pressure arising from the presence of an adsorptive force field. This is, of course, in addition to the usual freezing-point depression caused by dissolved material, which we are, for the present, neglecting. The freezing-point depression should also be expected to increase as more

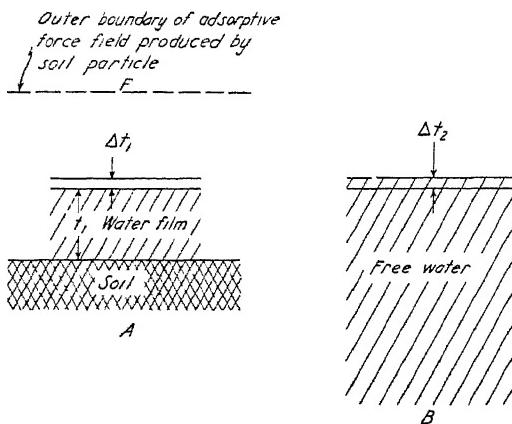


Fig. 36.—A, A radial section through a water-soil interface; B, a radial section through free, pure water.

and more soil moisture is frozen, because the hydrostatic pressure at the liquid-ice interface increases as the interface moves closer to the soil particle. This agrees qualitatively with the usual observations made in determining the freezing point of moist soil by the Beckmann method.

One might increase the hydrostatic pressure in  $\Delta t_2$  (by a piston, for example, or by any other external means) to the value found in  $\Delta t_1$  and consequently secure the same freezing-point depression for the two layers. Despite this equality of freezing-point depressions, the vapor pressures over the two layers would be quite different. The hydrostatic pressure produced by the piston on  $\Delta t_2$  will increase the vapor pressure (art. 41), which originally was already greater than that over  $\Delta t_1$  because of the presence of the adsorptive field surrounding the soil particle. Thus two layers of ice,  $\Delta t_1$  and  $\Delta t_2$ , may have the same freezing-point depression and yet possess widely different vapor pressures and consequently widely different free energies. The presence of the adsorptive force field surrounding the soil particle seems to account for this discrepancy of the

vapor pressures, although the freezing point of the water is the same in the two cases.

Because of the presence of the adsorptive force field, the escaping tendency of the water molecules from the soil moisture is reduced; consequently more work is required to carry a water molecule outward into the vapor phase against the adsorptive field of the soil, which is stronger than that of the free water. The velocities of the water molecules are distributed among the molecules according to the Maxwell distribution law (art. 54 and 55). Because of the adsorptive force field, those molecules having their velocities in the lower range of the Maxwell distribution are prevented from escaping into the vapor phase. The stronger the adsorptive force field, the larger the proportion of the slower molecules that are prevented from escaping. Not only will fewer molecules of the soil moisture be able to make the trip into the vapor phase, but those that do will be more inclined to return to the soil moisture because of the greater attractive influence exerted on them than when they are over free water. Thus, at equilibrium, there will be a smaller density of molecules over the moist soil than over the free-water surface. Since the average velocity is determined by temperature, which is the same for both  $\Delta t_1$  and  $\Delta t_2$ , then the vapor pressure will be higher over the free-water layer  $\Delta t_2$ .

We are led in consequence to the following considerations of the Beckmann method when used in determining the freezing point of soil moisture at relatively low moisture contents where there is relatively little water under tension.

The thicker the layer  $\Delta t$  of soil moisture we freeze out, the greater the hydrostatic pressure at the liquid-ice interface and consequently the greater the observed freezing-point depression (art. 63). When we determine the freezing point of soil moisture by the Beckmann method, we therefore should try to freeze as thin a layer of soil moisture  $\Delta t$  as possible, for we wish to find the freezing point of the moisture that is most loosely bound. It is the freezing point of the *outermost layer of infinitesimal thickness* that we are seeking when we wish to determine the freezing point of a body of soil moisture by the Beckmann method. It is always the first layer to freeze. We should therefore supercool the soil moisture only as much as is absolutely necessary before freezing is initiated; otherwise we shall obtain an erroneous value for the freezing-point depression, which is too low in proportion to the thickness of the layer frozen out. The freezing-point depression caused by the dissolved material is, of course, superimposed upon the depression just discussed.

At least three serious difficulties arise when one uses the Beckmann method for determining the freezing point of soil moisture at low moisture contents. Since the total thickness of the moisture film is small at the

lower moisture contents, the minimum thickness of the layer that can be frozen out in determining the freezing point of the soil moisture must be a large fraction of the total thickness of the layer of soil moisture. Thus the measured freezing-point depression is proportionately greater than that of the true value and really corresponds to a proportionately lower soil-moisture content than the true one. The discrepancies are further magnified because the intensity of the adsorptive force field increases very rapidly as the surface of the soil particle is approached, which causes very significant changes in the hydrostatic pressure within thin moisture films when their thickness is changed but slightly. Attempts, of course, are made to correct for the amount of ice frozen out. The corrections usually applied are probably inadequate, since they do not consider the effect of the ice on the hydrostatic pressure in the liquid next to the soil particle. The presence of the ice layer (art. 63) would be expected to lower the freezing point of the remaining unfrozen liquid below what it would be for the same amount of liquid if the ice were not present.

A second difficulty at the lower moisture contents arises because the freezing out of the thin layer of water  $\Delta t$  reduces the amount of solvent liquid water to a relatively great extent and therefore concentrates the soil-moisture solutes in the same proportion, so that the observed freezing-point depression becomes still lower than the true value.

The third difficulty with the Beckmann method at the lower moisture contents is that when we supercool the soil moisture as little as possible in order subsequently to freeze out as thin a layer of ice  $\Delta t$  as possible, the total latent heat of fusion required to melt the thin layer of ice is very small; and the soil moisture consequently may not hold the equilibrium temperature long enough to permit a dependable reading of the thermometer.

#### 69. Calculation of the Free Energy of Soil Moisture with Special Reference to the Interpretation of Dilatometer Measurements

There are several ways of measuring the free energy of soil moisture in relation to water retentiveness. The dilatometer method, however, seems to lend itself to a detailed analysis of the factors contributing to the total free energy of soil moisture, since we have developed a theory that enables us to consider the effect of each separate factor, such as dissolved material, adsorptive force field, and hydrostatic pressure.

As there is always an excess of water in the dilatometer, the freezing-point measurements made under these saturated conditions (where none of the water is under tension) must be interpreted in terms of the actual conditions found in the field or laboratory, where the soil is unsaturated. For this purpose, reference is made to figure 37. Part A of figure 37

represents a moist soil at some particular moisture content where the average thickness of the water film is  $t$ . We shall deal with a small enough radial section of moist soil so that the surface of the soil particle may be considered as flat. The figure at the right represents the same soil particle when placed in the dilatometer under conditions such that there is more than enough water to saturate the soil. The horizontal dotted line  $b$

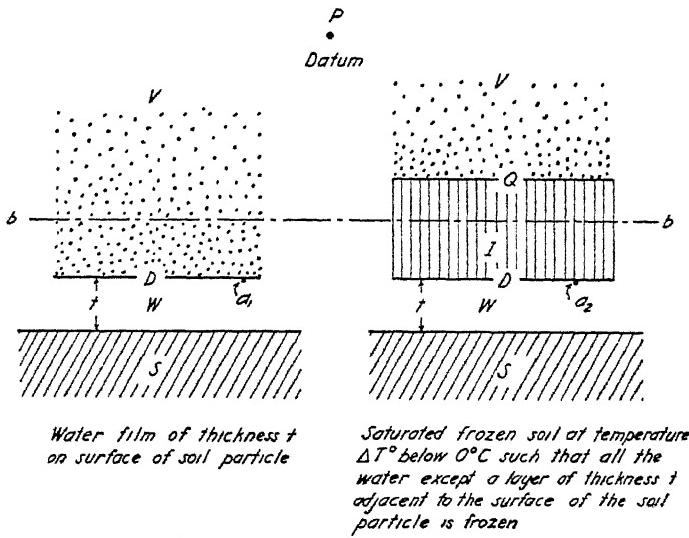


Fig. 37.—Comparison of conditions in moist soil outside and inside the dilatometer when the amount of unfrozen water in the dilatometer is the same as the actual soil moisture content in the soil outside the dilatometer.

crossing both figures represents schematically the outer boundary of the adsorptive force field, which, we postulate, surrounds the soil particles. We are here assuming that the temperature of the dilatometer containing the saturated soil (fig. 37, B) is at such a temperature  $\Delta T$  degrees below  $0^{\circ}\text{ C}$  that the amount of water remaining unfrozen just equals the moisture content of the moist soil represented in figure 37, A. In other words, the thickness  $t$  of the liquid water film covering the soil surface is the same in the two diagrams.

The customary standard of zero soil moisture content (which is usually regarded as the state of the soil reached after prolonged drying at  $110^{\circ}\text{ C}$ ) should probably not be used here in determining the amount of water in the film. It is found that as the temperature is raised to higher values than  $110^{\circ}\text{ C}$  (95) more adsorbed water is driven off. Here, we are concerned with all of the adsorbed water.

We seek now to represent the free energy of the soil moisture shown in figure 37, *A*, in terms of measurements of the total free energy of the unfrozen water in the dilatometer (fig. 37, *B*). To do this we shall first express the free energy  $\Delta f_s$  of the soil moisture in figure 37, *A*, in terms of its component free energies. We shall then represent the free energy  $\Delta f_D$  of the unfrozen water in figure 37, *B*, also in terms of its component free energies. Finally, we shall combine these two equations in such a way as to express the free energy of the soil moisture  $\Delta f_s$  in terms of the equivalent amount of unfrozen water and its freezing point in the dilatometer. We shall, in the future, represent this freezing point as  $\Delta T$  degrees below  $0^\circ \text{ C}$ . Often the freezing-point depression  $\Delta T$  is spoken of as the freezing point  $\Delta T$ .

*Free Energy  $\Delta f_s$  of Soil Moisture in Terms of Its Components.*—Starting now by considering figure 37, *A*, let  $\Delta f_s$  represent the total specific free energy of water. This is the same and a constant throughout both phases when the soil-moisture system has been allowed to reach equilibrium. Expressed in terms of vapor pressure,  $\Delta f_s$  may be represented (art. 39) by

$$\Delta f_s = RT \ln \frac{p_s}{p_0}. \quad (376)$$

This gives the free energy of the water in the soil-moisture system with reference to free, pure water at the same level as the moist soil, where  $p_s$  is the vapor pressure of the soil moisture, and  $p_0$  is the vapor pressure over a free water surface used as the datum. In other words,  $\Delta f_s$ , as expressed above, represents the work per gram of water that must be expended in a reversible process by some exterior agency in carrying a particle of water from free, pure water (the datum) whose vapor pressure is  $p_0$  to the moisture in the soil whose vapor pressure is  $p_s$ .

If  $\Delta f_s$  proves to be negative, energy or work is released to the exterior agency in the process of carrying water from free, pure water to any point in the soil moisture. That is, a gram of water as soil moisture would possess less energy than a gram of free, pure water, and therefore the free, pure water would spontaneously tend to pass into or flow into the moist soil.

The total free energy  $\Delta f_s$  of the soil moisture at any point in the liquid or vapor phase may be considered as a sum of several component free energies. Even though the soil moisture is in equilibrium and  $\Delta f_s$  is a constant throughout, the components of  $\Delta f_s$  may vary enormously from point to point in the soil moisture. Let us consider, for example, what these components of the free energy might be at the point  $a_1$ , immediately below the vapor-water interface (fig. 37, *A*). Three components must be considered.

A. Soil moisture has free energy  $\Delta f_{PS}$  due to the hydrostatic pressure exerted on it by the combined action of the atmosphere and any other external forces that might be transmitted to the air-water interface. The value of this pressure will be constant throughout the fluid, since such a pressure is transmitted uniformly throughout a liquid according to Pascal's law. In addition, the soil moisture at any point may have hydrostatic pressure because of the adsorptive field surrounding the soil particles. The field pulls the superincumbent water lying above the point in question towards the soil surface, and thereby produces a pressure similar to the hydrostatic pressure created in a body of water on the surface of the earth by the presence of the earth's gravitational field. At the point  $a_1$  under consideration (fig. 37, A), the compression produced by the field will be assumed to be zero, since there is no liquid farther out from the soil  $S$  to press against the liquid layer  $W$  and compress it.

The water at the air-water interface at the point  $a_1$ , for example, is under a hydrostatic pressure  $\Delta P_{PS}$  because of the pressure exerted by the atmosphere. The value of the free energy  $\Delta f_{PS}$  due to this pressure is given by  $\Delta f_{PS} = v \Delta P_{PS}$  (eq. 156), where  $v$  equals the specific volume of water (which in the c.g.s. system equals unity approximately) and where  $\Delta P_{PS}$  equals the total pressure acting on the water at the point in question. We then have

$$\Delta f_{PS} = 1 \times \Delta P_{PS} . \quad (377)$$

That is, the component of the free energy due to pressure is numerically equal to the hydrostatic pressure.

At the point  $a_1$  under consideration,  $\Delta P_{PS}$  is only 1 atmosphere, and no other external forces are acting upon the interface. If there were any,  $\Delta f_{PS}$  would be augmented by the additional amount. When, therefore, the soil moisture exists under the usual conditions, the pressure  $\Delta P_{PS}$  exerted on the water surface  $D$  is 1 atmosphere, and consequently

$$\Delta P_{PS} = 0.1 \times 10^7 \text{ dynes per sq. cm.}$$

So that

$$\Delta f_{PS} = 1 \times \Delta P_{PS} = 0.1 \times 10^7 \text{ ergs per gram of water.}$$

But according to the conventions presented in article 39, we must take

$$\Delta f_{PS} = 0 , \quad (378)$$

since only 1 atmosphere is acting on the air-water interface of the moist soil. This follows because of the peculiar conditions involved in the cus-

tomary definition of the freezing point of pure water and what we have taken as our datum (art. 39). To support this statement, we must recall that one external condition defining the freezing point of pure water, 0° C, is that the water is at a pressure of 1 atmosphere while freezing. Actually, if pure water could be frozen without any external force or pressure acting on it, its freezing point would be +0.0073° C, according to equation 187.

B. The free energy of soil moisture has another component,  $\Delta f_{os}$ , because it contains dissolved material. This component has, in previous literature (20, 103, 104), been called the "osmotic potential"; but for reasons mentioned earlier, the term "free energy" will be adhered to in this discussion.

If the osmotic pressure is  $\Delta P_{os}$  at  $a_1$  (fig. 37, A), then (art. 24)

$$\Delta f_{os} = -v \Delta P_{os}.$$

In the c.g.s. system the specific volume of water  $v$  is approximately equal to unity, and therefore

$$\Delta f_{os} = -1 \times \Delta P_{os}.$$

We notice that the zero point of the osmotic component of the specific free energy is taken as pure water, containing no dissolved material. Under this condition the osmotic pressure  $\Delta P_o$  equals zero. Also, we notice that unlike a positive hydrostatic pressure  $\Delta P_P$  (which increases the free energy of water), an osmotic pressure  $\Delta P_o$  decreases the potential of the water, as is indicated by the minus sign in the equation above, as well as by article 65. That is, dissolved material decreases, whereas positive hydrostatic pressure increases, the specific free energy of soil moisture.

The osmotic component of the free energy  $\Delta f_{os}$  of the water at the point  $a_1$ , which later will be shown to equal that at  $a_2$ , may be expressed in terms of the freezing-point depression  $\Delta T_{os}$  produced by the dissolved material, the osmotic pressure of which is  $\Delta P_{os}$ . By equation 200,

$$\Delta P_{os} = -\frac{l \Delta T_{os}}{vT} = -\frac{l \Delta T_{os}}{T}, \quad (379)$$

since  $v = 1$ , approximately, for water. Therefore (eq. 148), the osmotic component

$$\Delta f_{os} = +\frac{l \Delta T_{os}}{T}.$$

Thus if the freezing-point depression of a soil solution  $\Delta T_{os}$  due to osmotic pressure or dissolved material is determined, the osmotic component of the specific free energy of the soil moisture  $\Delta f_{os}$  can be found immediately.

C. Soil moisture possesses free energy also because it is situated in a field of force. The component of the free energy due to this cause will be designated by  $\Delta f_{FS}$  and will be called the component of the free energy due to the force field.

The component  $\Delta f_{FS}$  (art. 26), is roughly analogous to the gravitational potential of a particle above the earth's surface. As the particle is moved upwards against the earth's gravitational field, its gravitational potential increases. Upon its return to its original position, its potential energy is released. If it is allowed to fall freely, its gravitational potential will be transformed into kinetic energy; if suddenly stopped, it will be transformed into heat. The symbols  $\Delta f_{FS}$  represent the component of the free energy possessed, for example, by water at  $a_1$  (fig. 37, A) by virtue of its position in the force field surrounding the soil particle. This might be due to any force field which may surround the soil particle and which acts on the water molecules, such as electric, magnetic, or gravitational. This would include any free energy due to orientation which the water molecules surrounding the soil particle may have.

For soil moisture we shall take, as in the past, for the datum of the free energy due to the field, any point  $P$  in free, pure water beyond the influence of the force field surrounding the soil particle. The outer range of influence of the force field surrounding the soil particle is schematically represented by the line  $bb$  in figure 37. The free energy of the soil moisture  $\Delta f_{FS}$  at the point  $a_1$  is then the work required per gram to carry water from free, pure water to  $a_1$ . Because the water particles tend to move towards the soil surface and because mechanical energy is released in doing so,  $\Delta f_{FS}$  is always negative for soils except at the datum, where it is zero.

We have considered in detail three of the most important components of free energy  $\Delta f_s$  of soil moisture. Let us now combine them so as to obtain the resultant. The free energy  $\Delta f_s$  of the soil moisture is the sum of the component free energies

$$\Delta f_s = \Delta f_{PS} + \Delta f_{os} + \Delta f_{FS}. \quad (380)$$

Since the soil moisture is in equilibrium,  $\Delta f_s$  is a constant and the same at all points throughout the liquid and vapor phases (art. 22) as long as the moisture content remains the same, which in figure 37, A, means that the thickness  $t$  of the liquid layer remains constant. This follows

directly from the thermodynamic properties of free energy (art. 22). On the other hand, the three partial or component free energies may change enormously from point to point in the soil moisture. For example, if we assume that  $\Delta f_{os}$  is constant throughout the soil moisture, the component of the free energy due to the field  $\Delta f_{FS}$  will decrease as the soil surface is approached, while the component of the free energy due to hydrostatic pressure  $\Delta f_{PS}$  will increase in such a way as to keep the total free energy  $\Delta f_S$  constant. We shall wish to evaluate the total free energy  $\Delta f_S$  in terms of its partial or component free energies at the point  $a_1$  just under the vapor-water interface.

Our object is now to determine the total free energy  $\Delta f_S$  of soil moisture at a given moisture content in terms of the total free energy of the soil moisture in the dilatometer  $\Delta f_D$  (which in turn is expressed in terms of the three following partial free energies: that due to the hydrostatic pressure  $\Delta f_{PD}$ , that due to the osmotic pressure  $\Delta f_{oD}$ , and that due to the adsorptive force field  $\Delta f_{FD}$ ), obtained from freezing-point measurements made with the dilatometer on a saturated sample of the soil. This determination can, as we shall see, be made, provided we know the freezing point  $\Delta T$  at which the amount of unfrozen moisture remaining in the dilatometer (fig. 37, *B*) equals the moisture content of the soil in question (fig. 37, *A*). In other words, we require the freezing-point depression  $\Delta T$  in order that the thickness  $t$  of the unfrozen water (fig. 37, *B*) may be equal to the thickness of the soil-moisture film (fig. 37, *A*). The reason for making the amount of unfrozen water equal in the two parallel cases will become apparent later.

*Free Energy  $\Delta f_D$  of the Unfrozen Water in the Dilatometer Expressed in Terms of Its Components.*—Before we can express  $\Delta f_S$  of the moist soil in terms of data obtained from the dilatometer, we shall obtain an expression for the total free energy  $\Delta f_D$  of the soil moisture in the dilatometer, in terms of its component free energies. This will require a detailed consideration of the component free energies of  $\Delta f_D$ .

Figure 37, *B*, represents a small portion of a radial section of a soil particle with a liquid layer of thickness  $t$  overlain by an ice layer *I* and by water vapor *V*. The outer boundary of the influence of the adsorptive force field surrounding the soil particle is schematically represented by the line *bb*. Any water lying beyond this line is free from the body forces exerted by the soil particle. Since the point  $a_1$  (fig. 37, *B*) is within *bb*, it will be affected by the attractive force surrounding the soil particle.

Let us express  $\Delta f_D$ , the total free energy of water in any of the three phases, in terms of its components at the point  $a_1$  in the liquid adjacent to the water-ice interface *D*. Let  $\Delta f_D$  equal the total free energy of the water in figure 37, *B*, under the conditions assumed in figure 37, *A*. The

value of  $\Delta f_D$  is a constant and the same throughout all the three phases (liquid, ice, and vapor) when the system is at equilibrium, because of the thermodynamic properties of free energy (art. 22). Expressed in terms of the vapor pressure of the vapor phase,  $\Delta f_D$  may (art. 22 and 39) be represented by

$$\Delta f_D = RT \ln \frac{p_D}{p_0}. \quad (381)$$

Like  $\Delta f_s$ ,  $\Delta f_D$  is measured with respect to the point  $P$  in free, pure water, which is our datum;  $p_D$  denotes the vapor pressure of the ice at the temperature  $T_D$  of the partially frozen soil moisture in the dilatometer, and  $p_0$  denotes the vapor pressure of the pure, supercooled water at the same temperature  $T_D$ .

We shall now consider in detail (fig. 37, B) the three component free energies that go to make up  $\Delta f_D$  at the point  $a_2$  in the water layer adjacent to the water-ice interface.

A. Let  $\Delta f_{PD}$  represent the component free energy due to hydrostatic pressure exerted on the unfrozen water layer of thickness  $t$ . This component is due to two factors. One of these is the force or "weight" of the superincumbent ice between  $D$  and  $bb$  which lies within the influence of the adsorptive force field and which presses against the liquid water layer of thickness  $t$  (art. 64). This hydrostatic pressure in the soil moisture is analogous mechanically to the hydrostatic pressure found below the surface of a body of water in a reservoir. In the water of the reservoir, the hydrostatic pressure is produced by the weight of the overlying water arising from the presence of the earth's gravitational field. In soil moisture, the hydrostatic pressure arises from the presence of an adsorptive force field surrounding the soil particle. The other factor that contributes to  $\Delta f_{PD}$  is the atmospheric pressure exerted on the air-ice interface and communicated, in turn, to the water-ice interface.

The combined hydrostatic pressure  $\Delta P_{PD}$  due to both of the pressures mentioned above produces a freezing-point depression  $\Delta T_P$  of the soil moisture at the water-ice interface, in accordance with the Clausius-Clapeyron equation (art. 27)

$$\Delta P = \frac{l \Delta T_P}{T \Delta v}.$$

We find (eq. 156) that

$$\Delta f_{PD} = v \Delta P = v \frac{l \Delta T_P}{T \Delta v} = \frac{l \Delta T_P}{T \Delta v} \times 1, \quad (382)$$

since  $v = 1$ , approximately, in the c.g.s. system. Thus a determination of the freezing-point depression  $\Delta T_P$  due to the hydrostatic pressure of the

water at  $a_2$  lying in the water-ice interface (fig. 37, *B*) will immediately determine the component free energy  $\Delta f_{PD}$  of the water at the water-ice interface, since all the other quantities in equation 382 are well-known constants.

If dissolved salts are present in the liquid water layer of thickness  $t$  (fig. 37, *B*), the total freezing-point depression  $\Delta T$  of the water at  $a_2$  adjacent to the water-ice interface in the dilatometer will have two components:  $\Delta T_P$ , due to hydrostatic pressure just discussed; and  $\Delta T_O$ , due to the osmotic pressure of the dissolved material within the unfrozen water layer to be considered below. As will be recalled (art. 65), although hydrostatic pressure and dissolved material both produce freezing-point depressions of the soil water, whose combined freezing-point depression is the arithmetical sum of both, positive hydrostatic pressure gives soil moisture a positive component free energy, whereas dissolved material gives water a negative component free energy. Thus the component freezing-point depressions  $\Delta T_P$  and  $\Delta T_O$  are additive; but the component free energies  $\Delta f_P$  and  $\Delta f_O$  are subtractive, tending to neutralize each other (art. 65).

*B.* Let  $\Delta f_{OD}$  represent the component free energy of the water at  $a_2$  of figure 37, *B*, possessed because of the dissolved material. The same considerations apply to  $\Delta f_{OD}$  as were made for  $\Delta f_{OS}$ . Therefore  $\Delta f_{OD} = + \frac{l \Delta T_{OD}}{T}$

where  $\Delta T_{OD}$  represents the component freezing-point depression of the water at  $a_2$  in the water-ice interface because of the dissolved material.

Suppose a very small layer of water at the interface *D* (small as compared with the total thickness of the water film) is frozen and removed from solution. This procedure will concentrate the solute in the remaining liquid soil moisture, increasing its osmotic pressure  $\Delta P_{OD}$  as well as its freezing-point depression  $\Delta T_{OD}$ . Assuming for the present that the solutes are uniformly distributed throughout the liquid soil moisture, then if half the liquid layer is frozen, the osmotic pressure  $\Delta P_{OD}$  as well as the freezing-point depression  $\Delta T_{OD}$  of the remaining liquid will be doubled. Thus the relation between the volume of the unfrozen moisture and its osmotic pressure will follow van't Hoff's law (eq. 226). Because of the hypothesis above, as more of the soil moisture is frozen, the osmotic pressure  $\Delta P_{OD}$ , together with the freezing-point depression  $\Delta T_{OD}$  of the unfrozen moisture, should be expected to increase approximately in accordance with the following equations:

$$\begin{aligned} & (\text{amount of soil moisture still unfrozen}) \times (\text{osmotic pressure } \Delta P_{OD}) \\ & \quad = (\text{a constant at a specific temperature}) \end{aligned}$$

$$\begin{aligned} & (\text{amount of soil moisture still unfrozen}) \times (\text{freezing-point depression } \Delta T_{OD}) \\ & \quad = (\text{a constant at a specific temperature}). \end{aligned}$$

It is generally conceded, however, that the solute concentration increases as one approaches the soil-particle surface. Therefore, as the amount of solvent or liquid water is decreased by the gradual freezing out of soil moisture, one might expect the osmotic pressure  $\Delta P_{OD}$  as well as the freezing-point depression  $\Delta T_{OD}$  to increase more rapidly than is predicted by the equations above. To a first approximation, however, we shall assume the above equations. Further work with the dilatometer should shed more light on their validity.

Thus if the temperature of the saturated soil in the dilatometer is lowered so as to freeze part of the soil moisture, the part of the freezing-point depression due to dissolved material,  $\Delta T_{OD}$ , determines the osmotic pressure  $\Delta P_{OD}$  (eq. 200) and therefore the osmotic component of the free energy  $\Delta f_{OD}$  of the soil solution at the water-ice interface  $D$  of figure 37, *B*, in accordance with equation 148.

Since we have postulated that the thickness  $t$  of the unfrozen or liquid water layer surrounding the soil particle in the dilatometer (fig. 37, *B*) is the same as the thickness of the moisture layer surrounding the soil particle outside (fig. 37, *A*), we should expect that

$$\Delta f_{OS} = \Delta f_{OD} \quad (383)$$

since there is, to a first approximation, the same amount of liquid water as well as dissolved material present in the two cases.

C. Let  $\Delta f_{FD}$  represent the component free energy possessed by the water at  $a_2$  (fig. 37, *B*), arising because it is situated within the adsorptive force field surrounding the soil particle (art. 26 and 64). Comparing  $\Delta f_{FD}$  and  $\Delta f_{PD}$  above, one may say that  $\Delta f_{FD}$  is the component free energy possessed by water at  $a_2$  by virtue of its *position* in the adsorptive force field, whereas  $\Delta f_{PD}$  is the component possessed by water at  $a_2$  by virtue of the *hydrostatic pressure* there, arising in part from the presence of the force field surrounding the soil particle and acting on the superincumbent ice layer, and in part from external agencies such as atmospheric pressure. As was mentioned for  $\Delta f_{FS}$ , the free energy  $\Delta f_{FD}$  due to the adsorptive force field is roughly analogous to the gravitational potential possessed by a mass in the earth's gravitational field. All the considerations mentioned in connection with  $\Delta f_{FS}$  apply here to  $\Delta f_{FD}$ . But in addition,  $\Delta f_{FD}$  includes any effect of the adsorptive field surrounding the ice, which effect we shall represent by  $K$ . Since the points  $a_1$  and  $a_2$  are at the same distance  $t$  from the surface of the soil particles, we may, for reasons that will follow, write

$$\Delta f_{FD} = \Delta f_{FS} + K. \quad (384)$$

Since  $K$  will enter into the final expression for the total specific free energy of the soil moisture  $\Delta f_S$ , we had better consider its meaning in more detail and evaluate it. Consider again figure 37. As will be recalled, the datum for the free energy is taken as any point (here schematically represented by the point  $P$ ) in free, pure water outside the influence of the adsorptive force field. The total free energy  $\Delta f_{FS}$  at  $a_1$  in the soil moisture represents the work per gram of water required to carry water from the point  $P$  to  $a_1$  against the force of the adsorptive field surrounding the soil particle. Since water is attracted toward  $a_1$ , mechanical energy is released by the water in moving it from  $P$  to  $a_1$ . Consequently  $\Delta f_{FS}$ , the component of the free energy due to the adsorptive force field, will be inherently negative (eq. 168).

Let us now evaluate the component of the free energy  $\Delta f_{FD}$  at the point  $a_2$  in the water of the water-ice interface of the dilatometer. It will be shown, as stated by equation 384, that  $\Delta f_{FD}$  may be considered as made up of two parts, one of which is  $\Delta f_{PS}$ . In  $A$  of figure 37,  $\Delta f_{FS}$  represents the component free energy produced by the adsorptive force field surrounding the soil particle. In  $B$  of figure 37,  $\Delta f_{FS}$  is only part of  $\Delta f_{FD}$ . The other part,  $K$ , of  $\Delta f_{FD}$  arises from the presence of the adsorptive force field produced by the superincumbent ice layer that acts upon the water at  $a_2$ . The term  $\Delta f_{FS}$  is therefore the work per gram required to carry water from the point  $P$  to the point  $a_1$  or from  $P$  to the point  $a_2$  against the adsorptive force field produced only by the soil particle, neglecting the effect of the ice layer at  $a_2$ . This follows because  $a_1$  and  $a_2$  were assumed to be the same distance  $t$  from the soil-particle surface.

The second part of  $\Delta f_{FD}$ , which we shall call  $K$ , is therefore the work per gram of water required to carry the water from the point  $P$  to the point  $a_2$  through the adsorptive force field produced by the ice layer only. In other words, the force field at  $a_2$  differs from that at  $a_1$  only in that  $a_2$  is acted upon by the additional adsorptive force field produced by the ice layer. Since the soil in the dilatometer is always saturated, the ice layer will, in general, be so thick that  $K$  is independent of the amount of unfrozen water and ice present. Only when the thickness of the ice layer becomes such that its outer boundary  $Q$  falls inside the range of influence  $bb$  of the force field surrounding a soil particle will  $K$  change—that is, begin to decrease. One may then consider  $K$  as a constant representing the work per gram of water required in carrying water from the point  $P$ , through the adsorptive force field produced only by the ice, to the surface of the ice layer. Since it is a general characteristic of free energy that the total free energy at a point equals the sum of the components, we have immediately

$$\Delta f_{FD} = \Delta f_{FS} + K.$$

This follows because, although superimposed force fields are added vectorially, the associated free energies are added as scalars. Thus the total free energy due to the force field  $\Delta f_{FD}$  at  $a_2$  has been split up into two parts: (1) the work per gram  $\Delta f_{FS}$  required to carry water from the point  $P$  to  $a_2$  through the adsorptive force field produced only by the soil particle, and (2) the work per gram of water  $K$  required to carry water from  $P$  to  $a_2$  through the adsorptive force field produced only by the superincumbent ice layer. Since the thickness of the liquid layer is the same in the case of both  $A$  and  $B$  of figure 37, any effect of  $\Delta f_{FS}$  will be found to cancel out in the end. It might at first have seemed strange to split  $\Delta f_{FD}$  into two parts, one of which is  $\Delta f_{FS}$ ; but it was merely a mathematical artifice permitting us to reduce the number of unknown variables. If we know  $\Delta f_{FS}$ , we can now determine  $\Delta f_{FD}$  immediately, except for the universal constant  $K$ .

The free energy  $\Delta f_D$  of the moisture in the dilatometer is then the sum of three component free energies just considered in detail:

$$\Delta f_D = \Delta f_{PD} + \Delta f_{OD} + \Delta f_{FD}. \quad (385)$$

Since we have assumed that the soil moisture in the dilatometer is in equilibrium, the total free energy  $\Delta f_D$  must be a constant having the same value at all points throughout the liquid, ice, and vapor phases so long as the thickness  $t$  of the liquid layer remains the same. This is true even though the three component free energies may change enormously from one point to another in the soil moisture or in going from one phase to the other. No matter how they vary among themselves, their sum, under equilibrium conditions of the soil moisture, is a constant. This follows immediately from a consideration of the thermodynamic properties of the free-energy function (art. 22).

By using equations 380 and 385, we can now express the total free energy  $\Delta f_S$  of the moist soil at a given moisture content in terms of a freezing-point measurement made on a similar sample of saturated soil placed in the dilatometer.

Referring again to figure 37,  $A$ , we have (as has previously been shown at the point  $a_1$  in the moist soil)

$$\Delta f_S = \Delta f_{PS} + \Delta f_{OS} + \Delta f_{FS}. \quad (386)$$

At a like position  $a_2$  in the saturated soil (fig. 37,  $B$ ) in the dilatometer,

$$\Delta f_D = \Delta f_{PD} + \Delta f_{OD} + \Delta f_{FD}. \quad (387)$$

Also, since we have the same amount of liquid water surrounding the soil particles in the two cases (permitting the reasonable assumption that the concentrations are the same in both cases, as previously mentioned) and since  $a_1$  and  $a_2$  are at the same distance from the surface of the soil particles, we have equations 383 and 384 giving the free energy due to the osmotic pressure and the field, respectively:

$$\Delta f_{OD} = \Delta f_{OS}; \quad (388)$$

$$\Delta f_{FD} = \Delta f_{FS} + K. \quad (389)$$

With the aid of these two equations, equation 387 becomes

$$\Delta f_D = \Delta f_{PD} + \Delta f_{OS} + \Delta f_{FS} + K. \quad (390)$$

Therefore, combining equations 386 and 390 by equating ( $\Delta f_{OS} + \Delta f_{FS}$ ) of the former to ( $\Delta f_{OS} + \Delta f_{FS}$ ) of the latter, we have

$$\Delta f_S = \Delta f_D - \Delta f_{PD} + \Delta f_{FS} - K. \quad (391)$$

In our present case,  $\Delta f_{FS} = 0$  (eq. 378). This follows (as was explained before where  $\Delta f_{FS}$  was considered in detail) because of the peculiar conditions involved in the customary definition of the freezing point of pure water as well as the definition of  $0^\circ C$  and because the only pressure acting on the soil moisture at the air-water interface is 1 atmosphere. The free energy of the soil moisture then becomes

$$\Delta f_S = \Delta f_D - \Delta f_{PD} - K. \quad (392)$$

Also, because of our method of defining  $0^\circ C$ , the hydrostatic pressure to be used in evaluating  $\Delta f_{PD}$  at any point in the dilatometer is the total hydrostatic pressure at that point minus 1 atmosphere. If, then, the dilatometer contents are open to a pressure of 1 atmosphere, as is usually the case, then  $\Delta f_{PD}$  is due entirely to the hydrostatic pressure caused by the adsorptive field surrounding the soil particle.

The terms  $\Delta f_D$  and  $\Delta f_{PD}$  (eq. 392) can be expressed in terms of measurable quantities such as temperature and pressure, as was shown earlier in this article when  $\Delta f_D$  and  $\Delta f_{PD}$  were considered in detail. We have then

$$\Delta f_S = RT \ln \frac{p_D}{p_0} - \frac{l \Delta T_P}{T \Delta v} - K \quad (393)$$

where  $\Delta T_P$  is the freezing-point depression due only to hydrostatic pres-

sure in the soil moisture. This, of course, represents the difference between the total freezing-point depression  $\Delta T$  and that due to the presence of dissolved material  $\Delta T_o$  (art. 65).

We now wish to evaluate  $K$ . The term  $K$  is a constant and, as previously pointed out, is in general independent of the amount of unfrozen water in the dilatometer. Thus, whether one evaluates  $\Delta f_s$  for small or great amounts of unfrozen water,  $K$  should remain unchanged. If, then,  $K$  can be evaluated at some particular value of  $\Delta T_P$  in the equation above corresponding to a given amount of unfrozen moisture, it will have been determined for all others. We shall proceed to evaluate it in equation 393 at such a freezing-point depression  $\Delta T_P$  that the water-ice interface is beyond the influence of the adsorptive force field surrounding the soil particle—that is, beyond  $bb$  of figure 37, *B*.

Suppose  $\Delta f_s$  is evaluated for a moisture content (fig. 37, *A*) such that the thickness  $t$  of the unfrozen water layer is greater than the range of influence  $bb$  of the adsorptive force field exerted by the soil particle. We shall distinguish  $\Delta f_s$  under these conditions by  $\Delta f'_s$ . In this upper range of moisture contents, the freezing-point depression due to hydrostatic pressure  $\Delta T_P$  must equal zero, since the adsorptive force field surrounding the soil particle does not in this case extend out far enough to produce any hydrostatic pressure at the water-ice interface. Thus in this particular case the third term in equation 393 drops out, and we have

$$\Delta f'_s = RT \ln \frac{p_D}{p_0} - K. \quad (394)$$

Since, in order to evaluate  $K$ , we are considering a very wet soil (fig. 37, *A*) where  $t$  is very great, then the vapor pressure  $p_s$  of the soil moisture equals the vapor pressure  $P_D$  of the parallel case of the unfrozen water in the dilatometer (art. 22) when the interface  $D$  (fig. 37, *B*) lies above the plane  $bb$ . In other words,  $t$  extends beyond the adsorptive force field of the soil particle. Equation 394 then becomes

$$\Delta f'_s = RT \ln \frac{p_s}{p_0} - K. \quad (395)$$

The term  $\Delta f'_s$  of the reduced equation 395 can readily be evaluated. Since the point  $a_2$  (fig. 37, *B*) is now assumed beyond the adsorptive force field, the only significant factor contributing to the free energy  $\Delta f'_s$  of the soil moisture is the osmotic pressure of the dissolved material in the soil solution. Hence, under these special conditions, the total freezing-point depression  $\Delta T$  must be the same at the air-water interface of the

moist soil as at the water-ice interface in the dilatometer. Thus since  $\Delta f_s'$  is produced entirely by dissolved material, we may (eq. 207) express  $\Delta f_s'$  in still another way:

$$\Delta f_s' = \frac{l \Delta T}{T}. \quad (396)$$

Combining equations 395 and 396 we get:

$$\frac{l \Delta T}{T} = RT \ln \frac{p_s}{p_0} - K. \quad (397)$$

But

$$RT \ln \frac{p_s}{p_0} = + \frac{l \Delta T}{T} \quad (398)$$

since (eq. 236 and 207) the two members of equation 398 are merely two ways of expressing the free energy of the same solution due to the presence of dissolved material and since the concentrations of the soil solutions of both A and B of figure 37 are the same to a first approximation. The first member expresses the free energy of the solution in terms of its vapor pressure; the second, in terms of its freezing-point depression. Thus (eq. 398) the two terms of equation 397 cancel out, and we find

$$K = 0.$$

The free energy (eq. 393) of soil moisture at a particular soil moisture content, as determined from freezing-point measurements carried out with the dilatometer, takes on the final form

$$\Delta f_s = RT \ln \frac{p_D}{p_0} - \frac{l \Delta T_P}{T \Delta v}. \quad (399)$$

Here it is recalled that:

$T$  = temperature of the dilatometer corresponding to the total freezing-point depression  $\Delta T$  necessary to freeze out all but an amount of moisture equal to the soil moisture content whose free energy is desired (fig. 37).

$\Delta T_P$  = the part of the total freezing-point depression  $\Delta T$  in the dilatometer due to hydrostatic pressure alone; since this is a depression, it will be substituted as a negative quantity numerically. The value of  $\Delta T_P$  is determined from the total freezing-point depression measured with the dilatometer by subtracting from the latter the freezing-point depression produced by the

dissolved material. The latter is readily determined at each temperature from a knowledge of the freezing-point depression of the unfrozen soil solution in the dilatometer and the amount of unfrozen water shown by the dilatometer at each temperature.

- $p_D$  = the vapor pressure of the ice in the dilatometer at the temperature  $T$ .
- $p_0$  = the vapor pressure of supercooled water at the temperature  $T$ .
- $R$  = gas constant per gram of water.
- $l$  = heat of fusion of water which must be taken as negative if  $\Delta v$  is taken as positive.
- $\Delta v$  = volume change when 1 gram of water changes to ice; since water expands on freezing,  $\Delta v$  will be positive.

As will be recalled (following eq. 186), the ratio  $\frac{l}{\Delta v}$  is always negative; and since the freezing point  $T$  of soil moisture is always less than 0° C,  $\Delta T_P$  is also always negative. The quantity  $\Delta f_s$  (eq. 399) is therefore composed of two negative terms.

This equation permits us to evaluate the free energy  $\Delta f_s$  of soil moisture, at a particular moisture content, from freezing-point measurements made with a dilatometer. A series of such evaluations will be reported by the authors in a separate publication.

#### 70. Heat of Wetting and Swelling of Soils

When any dry substance, such as a soil, containing colloidal material is wetted, several phenomena are observed. There is usually a change in color, an increase in volume, and an increase in temperature. Since heat is developed at the same time that a change in volume takes place, physical chemists and botanists have devoted considerable attention to what has been called "heat of swelling." The differential heat of swelling  $\left(\frac{\partial q}{\partial V}\right)_T$  is the heat developed  $\partial q$  when the volume of the material wetted by the liquid changes by an amount  $\partial V$ . The subscript  $T$  is added to indicate that the initial and final temperature must be the same during the determination of  $\partial q$ . The differential heat of swelling increases rapidly as the moisture content of the substance being wetted decreases.

The differential heat of swelling  $\left(\frac{\partial q}{\partial V}\right)_T$  is closely related to the differential heat of wetting  $\left(\frac{\partial q}{\partial m}\right)_T$ . This relation will be discussed later. The differential heat of wetting of a soil at a particular moisture content may

be defined as the ratio of the heat developed  $\partial q$  to the mass of water  $\partial m$ , added uniformly throughout to a large amount of the moist soil already at the moisture content  $m$ . We note that enough soil is taken so that the amount of water  $\partial m$  added to the moist soil does not change the soil moisture content appreciably. If we take a very large amount of soil, the differential quotient is the heat developed when 1 gram of water is added and distributed uniformly throughout the large mass of soil.

The differential heat of wetting  $\left(\frac{\partial q}{\partial m}\right)_T$  may be measured in three

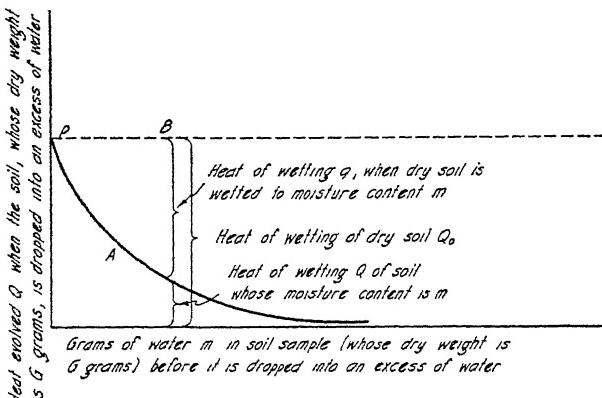


Fig. 38.—Integral heat of wetting of soils as a function of moisture content.

ways. In the first method, the material is wetted by adding a small increment of water  $\Delta m$  and measuring the quantity of heat  $\Delta q$  developed by the increment of moisture. This method, however, presents serious experimental difficulties: *It is impossible to make moisture distribute itself uniformly throughout a soil within a reasonable period at any moisture content below the moisture equivalent of the soil* (157, 158, 163); and it happens that the moisture equivalent always falls in the wet range of soil moisture contents, where the heat of wetting is practically zero. Such measurements, therefore, cannot well be made with reasonable accuracy at the moisture contents usually found in soils where plants are growing.

In the second method we prepare the soil sample at the desired moisture content in any of the standard ways. For example, we might spray a fine fog of water vapor over the dry soil and then enclose it in an airtight vessel until an equilibrium distribution of soil moisture is established. After the soil sample has reached equilibrium, suppose we drop it into a calorimeter containing an excess of water and measure the amount of heat  $Q$ , often called the *integral heat of wetting*, evolved by the soil sam-

ple, whose dry weight is  $G$  and which originally contained  $m$  grams of water. We can repeat the same procedure for a series of soil samples of varying moisture content  $m$ , and plot the results as shown by curve  $A$  (fig. 38). The vertical distance from the origin to the point  $P$  (where the point  $P$  is the intersection of curve  $A$  with the vertical axis) represents the amount of heat  $Q_0$  liberated when enough water is added to the dry soil to saturate it. The difference between  $Q_0$  and any other  $Q$ , associated with a particular moisture content  $m$ , represents the heat  $q$  liberated when dry soil is wetted uniformly to the particular moisture content  $m$ .

The slope  $\left(\frac{\partial q}{\partial m}\right)_T$  of this curve is the magnitude of the differential heat of wetting. The reason is readily seen if we draw a horizontal line  $B$  from  $P$ . We see from the curve that the more water  $m$  we add to the originally dry soil sample, the greater is the amount of heat  $q$  evolved.

The third method, which is indirect, uses the Clausius-Clapeyron equation:

$$l = T \left( \frac{dp}{dT} \right) (v_v - v_L), \quad (400)$$

as derived in article 27, where  $l$  represents the heat required to vaporize 1 gram of water (that is, the latent heat of vaporization) and where  $v_L$  and  $v_v$  are the specific volumes of liquid and vapor, respectively, at the vapor pressure  $p$ . Here  $(v_v - v_L) = \Delta v$  is the change in volume accompanying the change in phase from liquid to vapor. If  $v_L$  may be neglected in comparison with  $v_v$ , as is usually the case, we may write 400 in the form

$$l = T v_v \left( \frac{dp}{dT} \right). \quad (401)$$

If we may assume that the vapor obeys the perfect gas law, we may express  $v_v$  in terms of  $p$ ; and 401 becomes

$$l = \frac{RT^2}{p} \frac{dp}{dT} = RT^2 \frac{d \ln p}{dT}. \quad (402)$$

The latent heat of evaporation  $l$  is the negative of the heat of condensation or adsorption, which we shall denote by  $\lambda$ ; that is  $l = -\lambda$ . The heat of condensation  $\lambda$  is therefore the amount of heat liberated per gram of water vapor when the vapor condenses completely to the liquid state.

Expressed in terms of  $\lambda$ , equation 402 becomes

$$\lambda = -RT^2 \frac{d \ln p}{dT}.$$

We shall denote by  $\lambda_0$  the heat liberated per gram when water vapor condenses to the free, pure liquid state; and by  $\lambda$  the heat liberated per gram when water vapor condenses uniformly onto a large amount of soil already at a definite moisture content. We have, then, from the above, both

$$\lambda_0 = -RT^2 \frac{d \ln p_0}{dT} \quad \text{and} \quad \lambda = -RT^2 \frac{d \ln p}{dT}, \quad (403)$$

where  $p$  denotes the vapor pressure of the moist soil and  $p_0$  that of the free, pure water at the same temperature,  $T$ .

The heat of condensation or adsorption  $\lambda$  of soil moisture may be thought of as composed of two parts: (1) the heat liberated  $\lambda_0$  when 1 gram of water is condensed from the saturated vapor of the free liquid state; (2) the heat liberated when the same gram of water is taken from free, pure water and evenly distributed throughout a large mass of the soil at the moisture content at which we wish to determine the differential heat of wetting. To be strictly correct we should take so large an amount of soil that the addition of the gram of water will not alter the moisture content appreciably. The second part of the above is recognized immediately to be the differential heat of wetting  $\left(\frac{\partial q}{\partial m}\right)_T$ . Therefore

$$\lambda = \lambda_0 + \left(\frac{\partial q}{\partial m}\right)_T$$

or

$$\left(\frac{\partial q}{\partial m}\right)_T = \lambda - \lambda_0,$$

which with 403 becomes

$$\begin{aligned} \left(\frac{\partial q}{\partial m}\right)_T &= -RT^2 \frac{d \ln p}{dT} + RT^2 \frac{d \ln p_0}{dT} \\ &= RT^2 \frac{d(\ln p_0 - \ln p)}{dT} = RT^2 \frac{d \ln \left(\frac{p_0}{p}\right)}{dT} \end{aligned}$$

or, for small finite changes,

$$\left(\frac{\partial q}{\partial m}\right)_T = RT^2 \frac{\Delta \ln \left(\frac{p_0}{p}\right)}{\Delta T}. \quad (404)$$

Here the differential heat of wetting  $\left(\frac{\partial q}{\partial m}\right)_T$  denotes the heat liberated per gram of water added when pure water whose vapor pressure is  $p_0$  at

the temperature  $T$  is added to moist soil whose vapor pressure is  $p$  at the temperature  $T$ .

Equation 404 may, by a slight transformation, be adapted to the evaluation of the differential heat of wetting from measurements of vapor pressure of soil moisture at two different temperatures. If, therefore, the vapor pressures  $p_0$  and  $p$  of the free water and the moist soil, respectively, are measured at two different temperatures,  $T_1$  and  $T_2$ , we may write

$$\left(\frac{\partial q}{\partial m}\right)_T = \frac{RT_1 T_2 \left[ \ln\left(\frac{p_{02}}{p_2}\right) - \ln\left(\frac{p_{01}}{p_1}\right) \right]}{T_2 - T_1} \quad (405)$$

as representing a close approximation to the truth. Here we have resorted to the approximation of replacing the infinitesimal change of the logarithm of the pressures as well as the temperature by finite changes. This implies that the ratio of the finite changes is practically equal to the ratio of infinitesimal changes. At the same time, we have replaced  $T^2$  by  $T_1 T_2$  as being a very good average of  $T^2$  over the range for which the ratio is being determined. Thus, by measuring the vapor pressures  $p_1$  and  $p_2$  of the moist soil as well as the vapor pressures  $p_{01}$  and  $p_{02}$  of a free body of water at two different temperatures  $T_1$  and  $T_2$ , we can evaluate the differential heat of wetting  $\left(\frac{\partial q}{\partial m}\right)_T$ . Since the determination of the differential heat of wetting of a soil at a particular moisture content depends upon the measurement of the relative vapor pressure of a free body of water  $p_0$  with respect to that of the soil moisture  $p$ , evidently equation 405 is most useful in that range where  $p_0$  differs appreciably from  $p$ —that is, for relatively dry soils.

Finally, it is interesting to observe the close relation existing between the differential heat of wetting  $\left(\frac{\partial q}{\partial m}\right)_T$  and the differential heat of swelling  $\left(\frac{\partial q}{\partial V}\right)_T$ . As was proved in article 7, we may write

$$\left(\frac{\partial q}{\partial V}\right)_T = \left(\frac{\partial q}{\partial m}\right)_T \left(\frac{\partial m}{\partial V}\right)_T.$$

And according to article 6, the second term on the right may be transformed into its reciprocal, which is more readily visualized, giving

$$\left(\frac{\partial q}{\partial V}\right)_T = \frac{\left(\frac{\partial q}{\partial m}\right)_T}{\left(\frac{\partial m}{\partial V}\right)_T} \quad (406)$$

where  $\left(\frac{\partial V}{\partial m}\right)_T$  is the total increase of volume of our moist soil per unit mass of water added at a particular soil moisture content  $m$ , when the initial and final temperature during the process are kept the same, and a large enough amount of soil is taken so that the moisture content of the soil is not changed appreciably by the addition of the moisture. The volume here considered is the actual volume occupied by both soil and water *but does not include the volume occupied by air.*

If, as is frequently the case, no great change occurs in the total volume of the water and soil when water is added to the soil and if we use the c.g.s. system, we may set  $\left(\frac{\partial V}{\partial m}\right)_T = 1$ . Under these conditions, the heat of wetting would be numerically equal to the heat of swelling according to equation 406, which becomes

$$\left(\frac{\partial q}{\partial V}\right)_T = \left(\frac{\partial q}{\partial m}\right)_T. \quad (407)$$

We have then for the heat of swelling, according to 405 and 406,

$$\left(\frac{\partial q}{\partial V}\right)_T = \frac{RT_1T_2 \left[ \ln\left(\frac{p_{02}}{p_2}\right) - \ln\left(\frac{p_{01}}{p_1}\right) \right]}{(T_2 - T_1)} \left(\frac{\partial V}{\partial m}\right)_T. \quad (408)$$

And as mentioned above, if  $\left(\frac{\partial V}{\partial m}\right)_T = 1$ , approximately, in the c.g.s. system, equation 408 becomes

$$\left(\frac{\partial q}{\partial V}\right)_T = \frac{RT_1T_2 \left[ \ln\left(\frac{p_{02}}{p_2}\right) - \ln\left(\frac{p_{01}}{p_1}\right) \right]}{(T_2 - T_1)}, \quad (409)$$

enabling one to determine the heat of swelling of soil in terms of its vapor pressure at any two different temperatures,  $T_1$  and  $T_2$ . Equation 408 or 409 can be used easily only for comparatively dry soils, for the reasons given in connection with equation 405.

Incidentally,  $\left(\frac{\partial V}{\partial m}\right)_T$  is not exactly equal to 1, but departs from it slightly in drier soils.

### 71. Free Energy and Vapor Pressure of Soil Moisture in Relation to the Swelling Pressure of Soils

As will be recalled, the osmotic pressure of a solution is defined as the hydrostatic pressure  $\Delta P$  that must be placed on the solution to establish equilibrium between it and the pure solvent, through a semipermeable membrane—that is, to raise the vapor pressure or free energy of the solvent of the solution to that of the pure solvent. The swelling pressure of a colloid is defined in exactly the same way: it is the hydrostatic pressure  $\Delta P$  that must be applied to the water films surrounding the colloidal

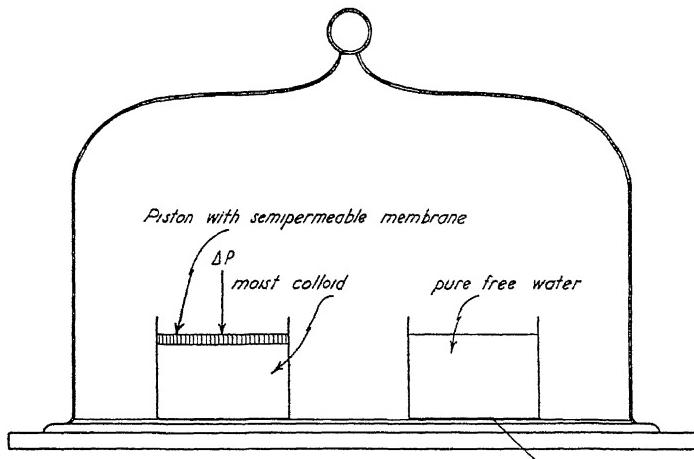


Fig. 39.—Moist colloid under the hydrostatic pressure necessary to make it in equilibrium with free, pure water.

particles in order to raise the vapor pressure of the colloid moisture to that of free, pure water at the same temperature.

One might even speak of the osmotic pressure of a colloid in analogy with that of a solution, as far as external appearances are concerned. Internally we should find the kinetic picture somewhat different. The vapor pressure of a solution is reduced by the solute particles in proportion to the ratio of the relative number of solute particles to solvent particles; that of a moist colloid, by the adsorptive forces surrounding the colloidal particles as well as by any solute that might be present in the colloid moisture.

Suppose the moisture in a colloid is at equilibrium with its vapor in a closed chamber (fig. 39). If a vessel of free water is brought into the chamber, the equilibrium will be disturbed, and the free water will distil onto the colloid because the vapor pressure or free energy of the free, pure water is greater than that of the colloid moisture. To restore equi-

librium in the chamber, we need only apply a hydrostatic pressure  $\Delta P$  to the colloid moisture (by means of a piston, permeable to vapor but not to liquid water) sufficient to raise its free energy and consequently its vapor pressure by the amount  $\Delta p$ , making the vapor pressure of the colloid moisture equal to that of the free, pure water. This particular change of the hydrostatic pressure  $\Delta P$  has been defined as the "swelling pressure."

As was shown in connection with equation 238 with the aid of equation 156 and article 22, the increase of the free energy  $\Delta f$  of a liquid as well as of its vapor (which, in the present case, is the colloid moisture) due to a hydrostatic pressure  $\Delta P$  on the liquid is given by

$$\Delta f = v_L \Delta P = v_V \Delta p. \quad (410)$$

Thus to increase the free energy of colloid moisture by the amount  $\Delta f$  to that of free, pure water we must exert a pressure  $\Delta P$  on the colloid moisture, which raises its vapor pressure by the amount  $\Delta p$ . Let  $\Delta P_c$  denote the hydrostatic pressure necessary to raise the vapor pressure  $p$  of the colloid moisture to that of free water  $p_0$ , in analogy with  $\Delta P_o$  for osmotic pressure.

The free energy of the colloid moisture, which we shall represent by  $\Delta f_c$ , is therefore a negative quantity equal to  $-\Delta f$  of equation 410, since we always measure free energies with respect to free, pure water. That is,

$$\Delta f_c = -\Delta f = -v_L \Delta P_c = -v_V \Delta p. \quad (411)$$

Thus if the swelling pressure in the colloid is  $\Delta P_c$ , the free energy  $\Delta f_c$  of the colloid moisture is  $-v_L \Delta P_c$ . Equation 411, by the way, has the same form as equation 151 for the free energy due to osmotic pressure.

We wish now to express the swelling pressure  $\Delta P_c$  in terms of the vapor pressure  $p$  of the colloid. From equation 411 we may write, for infinitesimal changes,

$$v_L dP_c = v_V dp.$$

Assuming that the vapor obeys the ideal gas law (eq. 367), we have

$$v_L \int_0^{\Delta P_c} dP_c = RT \int_p^{p_0} \frac{dp}{p}.$$

Integrating, we have

$$\Delta P_c = \frac{RT}{v_L} \ln \frac{p_0}{p};$$

or, by inverting the ratio  $\frac{p_0}{p}$ , we get

$$\Delta P_c = -\frac{RT}{v_L} \ln \frac{p}{p_0}. \quad (412)$$

It will be remembered that when we are dealing with water in the c.g.s. system,  $v_L = 1$ .

This, it might be noted, is identical in form with equation 251, giving the relation between hydrostatic pressure and vapor pressure, and particularly with the following equation, giving the relation between osmotic pressure and vapor pressure:

$$\Delta P_o = -1 \times \frac{RT}{v_L} \ln \frac{p}{p_0}.$$

The latter was obtained by combining equations 148 and 227.

Caution must be exercised in attempting to apply equation 412 experimentally to unsaturated soils where a force is applied to squeeze out water. In this case, part of the force applied to the soil mass may be transmitted through the solid particles by direct mechanical contact between them. Such a force contributes no hydrostatic pressure to the colloid moisture and should not be included with  $\Delta P_c$ , since it merely tends to break down the granules. The other part, representing the actual increase of hydrostatic pressure in the colloid moisture, represents the swelling pressure  $\Delta P_c$ . Only when all the pores of the colloid are completely filled with water can we be certain that the hydrostatic pressure necessary to just begin to squeeze out water from the colloid is equal to the swelling pressure  $\Delta P_c$  of the colloid, unless the pressure is applied by means of some inert fluid filling the space not occupied by moisture. Thus we see that if we are not careful, the hydrostatic pressure of the colloid moisture may have no relation to the force applied to the colloid externally, unless that force is applied through an inert fluid which fills up all the voids and transmits the pressure directly to the soil moisture.

To illustrate the application of these ideas, we might consider a concrete highway underlain by a very heavy clay soil into which moisture would tend to seep. Suppose some free water comes in contact with the clay subsoil. We might ask how great a pressure would be exerted upward on the pavement because of the tendency of the free water to move into the clay. We should find that the upward pressure is just the swelling pressure  $\Delta P_c$  we have been considering, and that  $p$  is the vapor pressure of the clay subsoil at the time the swelling pressure  $\Delta P_c$  is being determined.

# THEORY UNDERLYING THE CALCULATION OF THE ABSOLUTE VALUE OF THE FREE ENERGY $f$ OF SOIL MOISTURE AT ANY TEMPERATURE

## 72. General Treatment of the Dependence of Free-Energy Relations of Soil Moisture on Temperature

In all our foregoing considerations of the free energy  $\Delta f_s$  of soil moisture, we have been dealing with the difference between two absolute values of free energy  $f$  and  $f_0$  such that  $\Delta f_s = (f - f_0)$ . Here  $f_0$  equals the absolute value of the specific free energy of our datum, which is usually taken as free, pure water; and  $f$  represents the absolute value of the specific free energy of the soil moisture. In other words,  $\Delta f_s$  represents the energy, aside from the work of expansion against atmospheric pressure, that must be given to each gram of water to change it from its state in the soil moisture to that in free, pure water.

Parenthetically we may add that the datum need not be a free, pure body of water. Actually the water may be in any desired state. With few exceptions, however, free, pure water will be found to be the most convenient and desirable datum. Unless otherwise mentioned,  $f_0$  will therefore refer to the absolute value of the specific free energy of free, pure water.

It will be recalled that the specific free energy  $\Delta f_s$  is measured with both the datum and the soil moisture at the same temperature. Until now, nothing has been explicitly stated regarding the effect of a change of temperature either on the absolute specific free energies  $f$  and  $f_0$  or on  $\Delta f_s$  itself. It is important and interesting to determine this dependency. For example,  $\Delta f_s$  may be determined from freezing-point measurements on soil moisture, at a temperature near  $0^\circ \text{C}$ . It may, however, actually be desirable to know the specific free energy  $\Delta f_s$  of the soil moisture at some higher temperature in order, for example, to determine the amount of energy a plant must expend to extract water from the soil at a given moisture content. The question then is, how are we to find the specific free energy  $\Delta f_s$  at any temperature  $T$  when we have determined it once at some particular temperature  $T_0$ ? A satisfactory answer to this should greatly increase the range of usefulness of our known values of  $\Delta f_s$ . It will enable us to calculate  $\Delta f_s$  at any temperature  $T$  in terms of a single determination at some temperature  $T_0$ .

In order to fix in mind the relation between the absolute value of the specific free energy  $f$  and the specific free energy  $\Delta f_s$  and their dependency on temperature, let us consider with reference to a moist soil the schematic diagram shown in figure 40. The curve  $f_0$  indicates the variation of the absolute value of the specific free energy of free, pure water, our da-

tum, as the temperature is changed;  $f$  indicates the change of the absolute value of the specific free energy of soil moisture as the temperature is changed. The specific free energy  $\Delta f_{ST}$  of the soil moisture at the temperature  $T_1$  is given by the difference in ordinate between the curves at  $T_1$ ; that is,  $(f - f_0) = \Delta f_{ST_1}$ . The shape and values for the free-energy curves will of course depend upon the particular problem. As we proceed to a different temperature  $T_2$  of our soil moisture, both  $f_0$  and  $f_1$  change; and consequently the specific free energy changes to a new value,  $\Delta f_{ST_2}$ . We thus observe that in general  $\Delta f_S$  changes with the temperature.

As will be recalled (art. 62 and the latter part of art. 21) the specific

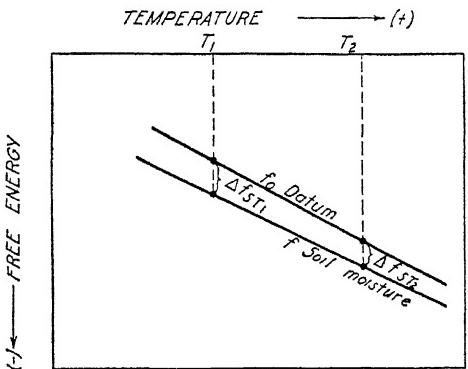


Fig. 40.—The change in free energy  $\Delta f_S$  with temperature.

free energy  $\Delta f$  has distinct advantages over the quantities total potential and capillary potential used previously in soil literature in describing the energy relations of soil moisture. Our present case is another excellent illustration of this fact. The quantities capillary potential and total potential were not defined in such a way as to show explicitly the dependence of these functions on temperature. The definition of free energy, on the other hand, involves the temperature explicitly (eq. 92). If we have determined the total or capillary potential of our soil-moisture system at one temperature, for example, the definition of these terms does not permit us conveniently to calculate the magnitude of these functions at any other temperature. We shall find, though, that the manner in which the term "free energy" has been defined enables us directly to show how the energy of soil moisture depends on the temperature.

Our problem in the articles to follow is therefore to calculate, on the basis of thermodynamics, the specific free energy  $\Delta f_{ST_2}$  of our soil moisture at any temperature  $T_2$  from a known value  $\Delta f_{ST_1}$  at a particular temperature  $T_1$ .

73. Dependence of the Absolute Value of the Free Energy  $f$  of Soil Moisture  
on the Temperature

In this article we shall derive by two different methods an expression showing how the absolute value of the free energy  $f$  of water varies with changes in temperature. Then, in later articles, we shall show how the difference  $(f_1 - f_0) = \Delta f_s$ , the free energy of soil moisture, varies with temperature. Thus the dependence of these functions of soil moisture on temperature will have been indicated.

*Method I.*—As already shown (art. 21), the free energy  $f$  is defined basically by

$$f = h - Ts. \quad (413)$$

From equation 91, the heat content  $h$  may be expressed by

$$h = \int_0^T c_p dT \quad (414)$$

where  $c_p$  denotes the specific heat at constant pressure and the integration is carried out from  $0^\circ A$  to  $T^\circ A$ . The entropy  $s$  (eq. 86), may be expressed by

$$s = \int_0^T \frac{c_p dT}{T}. \quad (415)$$

Thus equation 413 becomes

$$f = \int_0^T c_p dT - T \int_0^T \frac{c_p dT}{T}. \quad (416)$$

For our present purpose, let us evaluate  $f$  at the two temperatures  $T_1$  and  $T_2$ . As will be seen later,  $T_1$  will be taken as  $273^\circ A$ . At  $T_1$ , equation 416 takes on the following form:

$$f_1 = \int_0^{T_1} c_p dT - T_1 \int_0^{T_1} \frac{c_p dT}{T}; \quad (417)$$

and at  $T_2$

$$f_2 = \int_0^{T_2} c_p dT - T_2 \int_0^{T_2} \frac{c_p dT}{T}. \quad (418)$$

The integration of equation 418 from  $0^\circ A$  to  $T_2$  may be divided into two steps: an integration from  $0^\circ A$  to  $T_1$ , and then from  $T_1$  to  $T_2$ , giving

$$f_2 = \int_0^{T_1} c_p dT + \int_{T_1}^{T_2} c_p dT - T_2 \int_0^{T_1} \frac{c_p dT}{T} - T_2 \int_{T_1}^{T_2} \frac{c_p dT}{T}. \quad (419)$$

Subtracting equation 417 from 419, we have

$$f_2 - f_1 = \int_{T_1}^{T_2} c_p dT - T_2 \int_0^{T_1} \frac{c_p dT}{T} + T_1 \int_0^{T_1} \frac{c_p dT}{T} - T_2 \int_{T_1}^{T_2} \frac{c_p dT}{T}. \quad (420)$$

As shown by Nernst and others, the specific heat at constant pressure  $c_p$  decreases considerably as one approaches  $0^\circ A$ ; but in the neighborhood of  $T_1 = 273^\circ A$ , it is practically constant for water in the liquid phase (art. 20). Therefore  $c_p$  can be taken outside the integral sign of the first and last terms of the right-hand side of equation 420 since  $c_p$  is approximately constant within the limits of temperature determined by  $T_1$  and  $T_2$ ; and, as will be recalled (eq. 415), the integrals of the second and third terms above are  $T_2 s_1$  and  $T_1 s_1$ , respectively. Equation 420 accordingly becomes

$$f_2 - f_1 = c_p(T_2 - T_1) - s_1(T_2 - T_1) - T_2 c_p \int_{T_1}^{T_2} \frac{dT}{T}; \quad (421)$$

and therefore

$$f_2 - f_1 = c_p(T_2 - T_1) - s_1(T_2 - T_1) - T_2 c_p \ln \frac{T_2}{T_1}$$

and

$$\begin{aligned} f_2 &= f_1 + c_p(T_2 - T_1) - s_1(T_2 - T_1) - T_2 c_p \ln \frac{T_2}{T_1} \\ &= f_1 + (T_2 - T_1)(c_p - s_1) - T_2 c_p \ln \frac{T_2}{T_1}. \end{aligned} \quad (422)$$

This equation shows directly the dependence of the absolute value of the specific free energy of soil moisture on temperature. Knowing the absolute value of the free energy, specific heat, and entropy at one temperature  $T_1$ , we can calculate the absolute value of the free energy  $f_2$  of moisture at any other temperature  $T_2$ . As  $T_2$  approaches  $T_1$ ,  $f_2$  approaches  $f_1$ , a situation that is to be expected.

*Method II.*—To support the validity of equation 422 and to illustrate different possible general methods of applying thermodynamics to soil moisture, let us consider another approach to equation 422.

As shown in equation 143,

$$\left( \frac{\partial f}{\partial T} \right)_P = -s. \quad (423)$$

Now the specific entropy  $s$  (eq. 85) may be represented by

$$s = s_1 + \int_{T_1}^T \frac{c_p dT}{T}. \quad (424)$$

Here  $s_1$  is the absolute value of the entropy at the temperature  $T_1$ , which we shall put equal to  $273^\circ$  A. Since  $c_p$  is essentially constant (art. 20) with respect to changes of temperature in the vicinity of  $273^\circ$  A, we can take  $c_p$  outside of the integral sign; and therefore

$$s = s_1 + c_p \int_{T_1}^T \frac{dT}{T}. \quad (425)$$

Integrating, we have

$$s = s_1 + c_p \ln \frac{T}{T_1}. \quad (426)$$

Substituting  $s$  from equation 426 into equation 423, we get

$$\left( \frac{\partial f}{\partial T} \right)_P = -s = -s_1 - c_p \ln \frac{T}{T_1} = -s_1 - c_p \ln T + c_p \ln T_1. \quad (427)$$

Since we wish to deal with a definite integral from which the integration constant falls out, we may change the partial derivatives to total derivatives without altering the result, and obtain

$$df = -s_1 dT - c_p \ln T dT + c_p \ln T_1 dT. \quad (428)$$

Integrating 428, between  $T_1$  and  $T_2$ , we find

$$\begin{aligned} f_2 - f_1 &= -s_1 \int_{T_1}^{T_2} dT - c_p \int_{T_1}^{T_2} \ln T dT + c_p \ln T_1 \int_{T_1}^{T_2} dT \\ &= -s_1(T_2 - T_1) - c_p \left[ T \ln T - T \right]_{T_1}^{T_2} + c_p(T_2 - T_1) \ln T_1 \\ &= -s_1(T_2 - T_1) - c_p T_2 \ln T_2 + c_p T_2 + c_p T_1 \ln T_1 - c_p T_1 \\ &\quad + c_p(T_2 - T_1) \ln T_1. \end{aligned} \quad (429)$$

Cancelling out and combining terms,

$$\begin{aligned} f_2 - f_1 &= -s_1(T_2 - T_1) - c_p T_2 \ln \frac{T_2}{T_1} + c_p(T_2 - T_1) \\ &= (T_2 - T_1)(c_p - s_1) - c_p T_2 \ln \frac{T_2}{T_1} \end{aligned} \quad (430)$$

and

$$f_2 = f_1 + (T_2 - T_1)(c_p - s_1) - c_p T_2 \ln \frac{T_2}{T_1}, \quad (431)$$

which is the same equation as arrived at by method I.

To bring out one way in which equations 422 and 431 might be used for calculating the change in the absolute value of the free energy of moisture in going from one temperature,  $T_1$ , to another,  $T_2$ , let us assume, for example, that  $T_1 = 0^\circ \text{ C}$ , and  $T_2 = 25^\circ \text{ C}$ , and calculate the change in the absolute value of the specific free energy of free, pure water which we have taken as the datum (art. 39). From the *International Critical Tables* for pure water we find that at  $0^\circ \text{ C}$

$$\begin{aligned}f_1 &= -1.5985 \times 10^{11} \text{ ergs per gram;} \\s_1 &= 2.11 \times 10^7 \text{ ergs per degree per gram;} \\c_p &= 4.18 \times 10^7 \text{ ergs per gram.}\end{aligned}$$

Substituting these in equation 431 in order to calculate  $f_2$  at  $25^\circ \text{ C}$ , we have

$$\begin{aligned}f_2 &= -1.5985 \times 10^{11} + (298 - 273) (4.18 \times 10^7 - 2.11 \times 10^7) \\&\quad - 4.18 \times 10^7 \times 298 \times 2.3 \log \frac{298}{273} \\&= -1.5985 \times 10^{11} + 0.517 \times 10^9 - 1.092 \times 10^9 \\&= -1.6043 \times 10^{11} \text{ ergs per gram.}\end{aligned}$$

The *International Critical Tables* give as the free energy of water at  $25^\circ \text{ C}$

$$f_2 = -1.6060 \times 10^{11} \text{ ergs per gram.}$$

The calculated value of  $f_2$  at  $25^\circ \text{ C}$  is reasonably close to the one given by the *International Critical Tables*, which was determined experimentally.

It is interesting to calculate the total change in the absolute value of the free energy in going, for example, from  $T_1 = 0^\circ \text{ C}$  to  $T_2 = 25^\circ \text{ C}$ . From the values of  $f_2$  and  $f_1$  above we have

$$\begin{aligned}f_2 - f_1 &= (-1.6043 \times 10^{11}) - (-1.5985 \times 10^{11}) \\&= -58 \times 10^7 \text{ ergs per gram.}\end{aligned}$$

Thus the absolute free energy is decreased by  $58 \times 10^7$  ergs as the free, pure water goes from  $0^\circ \text{ C}$  to  $25^\circ \text{ C}$ . Suppose that the free energy  $\Delta f_s$  of soil moisture at the permanent wilting percentage is approximately  $-8 \times 10^7$  ergs per gram in the neighborhood of  $0^\circ \text{ C}$ .

These relations are schematically illustrated by figure 41, which, for clarity, is drawn to a distorted scale. The top curve represents the variation of the absolute value of free energy with temperature for free, pure water in ergs per gram. When the temperature of the free, pure water is

changed from  $273^{\circ}$  A to  $298^{\circ}$  A, the absolute value of the free energy of the free, pure water drops from *A* to *B*, which entails a drop of  $58 \times 10^7$  ergs per gram.

The variation, with changes in temperature, of the absolute value of the free energy *f* of soil moisture at a particular soil moisture content is represented by a curve such as *CD*. If *CD* corresponds to the moisture content at the permanent wilting percentage, then the curve for all moisture contents greater than this, such as the *moisture equivalent* or *field*

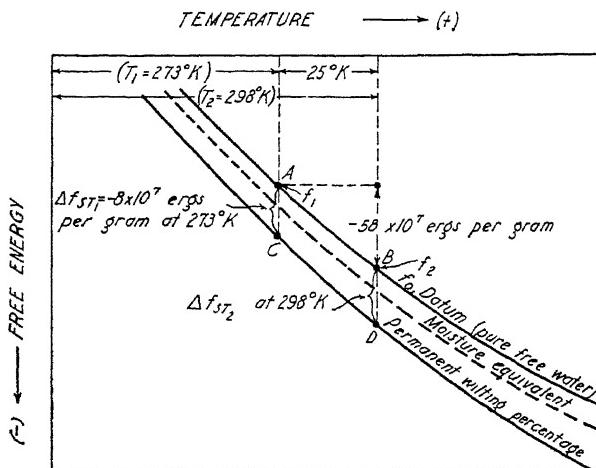


Fig. 41.—The variation of the free energy of soil moisture with temperature at the moisture equivalent and permanent wilting percentage.

*capacity*, will lie between *CD* and *AB*. If the soil is drier than the permanent wilting percentage, then the corresponding curve will lie below *CD*. Thus the absolute value of the specific free energy *f* of soil moisture for a given soil at different moisture contents is represented by a family of curves. Each member corresponds to a single value of the soil moisture content and shows the variation of the free energy *f* of the soil moisture with temperature.

The vertical distance between any two curves or members of the family, at a particular temperature, represents the difference in the absolute value of the free energy of the soil moisture at the two moisture contents. If one of the curves is that corresponding to free, pure water such as *AB* in the diagram, the vertical distance  $\Delta f_s$ , with respect to *AB*, is what we have previously called the "specific free energy" or just the "free energy" of the soil moisture. The assumed free energy  $\Delta f_{ST_1}$  at the temperature  $T_1$  of the soil moisture at the permanent wilting percentage

is represented by the distance  $AC$ , or  $-8 \times 10^7$  ergs per gram. As will be noticed from the discussion above, a change of 25 centigrade degrees causes a change in the absolute value of the free energy of the datum of  $-58 \times 10^7$  ergs per gram, whereas the difference in the absolute value of the free energy between the datum and soil moisture at the permanent wilting percentage at a constant temperature ( $T_1 = 273^\circ A$ ) is only  $-8 \times 10^7$  ergs per gram.

As the diagram indicates, the absolute free energy  $f$  changes rapidly with temperature. We have not yet shown quantitatively how  $\Delta f_s$  changes with temperature. If free energy of soil moisture  $\Delta f_s$  were independent of temperature, the two curves  $AB$  and  $CD$ , as well as all the other members of the family of curves, would be parallel to each other. This is not, in general, true, as will be discussed later. If, then, we have a sample of soil at a particular moisture content, the amount of work or effort a plant or any other mechanism must exert to remove water from the moist soil will in general vary with the temperature of removal.

## THEORY UNDERLYING THE CALCULATION OF THE FREE ENERGY $\Delta f_s$ OF SOIL MOISTURE AT ANY TEMPERATURE UNDER DIFFERENT CONDITIONS

### 74. Dependence of the Free Energy $\Delta f_s$ of Soil Moisture on Temperature, the Effect of Surface Tension $\sigma$ Only Being Considered

In the last article we considered the changes in the absolute value of the free energy  $f_0$  of our datum, with respect to variations of temperature. We found it to be appreciable. In fact, a change from 0° C to 25° C entailed a drop in the absolute value of the free energy of about  $58 \times 10^7$  ergs per gram.

We shall now consider the variation of the free energy  $\Delta f_s$  of soil moisture at a particular soil moisture content with variations of temperature. That is, we wish to study how the vertical distance between two curves such as  $AB$  and  $CD$  in figure 45 (p. 263) varies as we go from one temperature to another.

The determination of the dependency of  $\Delta f_s$  on temperature is extremely important. For example, as mentioned previously, our method of determining  $\Delta f_s$  at a particular soil moisture content may require us to determine it in the neighborhood of 0° C. Yet we might, for practical purposes, wish to use the value of  $\Delta f_s$  at 25°C—the temperature at which plant may be growing. Without knowing how  $\Delta f_s$  depends upon temperature, we should have to determine  $\Delta f_s$  experimentally at each temperature at which it is to be used.

We shall now turn to the case of a relatively moist soil where the effect on the air-water interface of the adsorptive force field surrounding the soil particle is negligible. The effect of dissolved material will be taken up later. The present treatment applies to determinations of the capillary potential made in the past by a porous bulb atmometer on soils whose moisture content falls in the vicinity of the field capacity or the moisture equivalent. Under the conditions here postulated, the capillary potential is practically synonymous with free energy, since the component of the free energy due to the adsorptive field is here negligible. The final mathematical expression we shall obtain for  $\Delta f_s$  will enable us to calculate  $\Delta f_s$  at any temperature from a single determination of  $\Delta f_s$  made at a particular temperature.

Let us assume that the free energy  $\Delta f_{ST_1}$  has been determined at a single temperature  $T_1$ , and endeavor to express the free energy  $\Delta f_s$  at any other temperature  $T$  in terms of  $\Delta f_{ST_1}$ . Under the conditions postulated, the variation of  $\Delta f_s$  with temperature is caused by the variation of the surface tension  $\sigma$  with temperature. Since the surface tension  $\sigma$  decreases with increase of the temperature  $T$ , we might expect the free energy

$\Delta f_s$  to decrease as the temperature  $T$  is raised. Quantitatively this is shown as follows:

From equation 211 we have the following relation connecting the surface tension  $\sigma$ , the free energy  $\Delta f_{ST}$ , and the radius of curvature  $r$  of the air-water interface of a capillary body of water at the temperature  $T$ :

$$\Delta f_{ST} = RT \ln \frac{p}{p_0} = \frac{2v \sigma_T}{r}. \quad (432)$$

Here  $p$  refers to the vapor pressure of the moist soil,  $p_0$  to that of free, pure water, both at the same temperature,  $T$ . Neither  $v$  nor  $r$  would be expected to change appreciably as the temperature of the moist soil changes, since the soil moisture content is kept constant throughout all changes of temperature in the present treatment. Of course, if the moisture content is not kept constant when the temperature is changed, there are other complications, not treated here. Since the magnitude of the radius of curvature  $r$  of the air-water interface of soil moisture is hard to determine directly, we shall eliminate it from equation 432.

Let us assume that at another temperature  $T_1$  the surface tension of water is  $\sigma_{T_1}$  and also that the free energy of the soil moisture has been determined and found to be  $\Delta f_{ST_1}$ . We then have (eq. 432)

$$\Delta f_{ST_1} = \frac{2v}{r} \sigma_{T_1}$$

so that

$$\frac{2v}{r} = \frac{\Delta f_{ST_1}}{\sigma_{T_1}}.$$

Hence equation 432 becomes

$$\Delta f_{ST} = RT \ln \frac{p}{p_0} = \left( \frac{\Delta f_{ST_1}}{\sigma_{T_1}} \right) \sigma_T. \quad (433)$$

Since we wish to express  $\Delta f_{ST}$  in terms of the temperature  $T$ , the surface tension  $\sigma_T$  must also be expressed in terms of  $T$ . The dependence of the surface tension  $\sigma_T$  on the temperature is given by figure 42, plotted from data taken from the *International Critical Tables*. From these data the following relation was derived:

$$\sigma_T = 117 - 0.152T \quad (434)$$

where the surface tension  $\sigma_T$  is expressed in dynes per centimeter, and the temperature  $T$  in degrees absolute.

Inserting  $\sigma_T$  of equation 434 in 433, we have

$$\Delta f_{ST} = RT \ln \frac{p}{p_0} = \left( \frac{\Delta f_{ST_1}}{\sigma_{T_1}} \right) (117 - 0.152T). \quad (435)$$

Equation 435 enables us to calculate the free energy  $\Delta f_{ST}$  at any temperature  $T$  in terms of a single determination of the free energy  $\Delta f_{ST_1}$  of the soil moisture, made at the temperature  $T_1$  according to

$$\Delta f_{ST} = \frac{\Delta f_{ST_1}}{\sigma_{T_1}} (117 - 0.152T). \quad (436)$$

The surface tension  $\sigma_{T_1}$  can, of course, be obtained from equation 434 or directly from a set of physical tables.

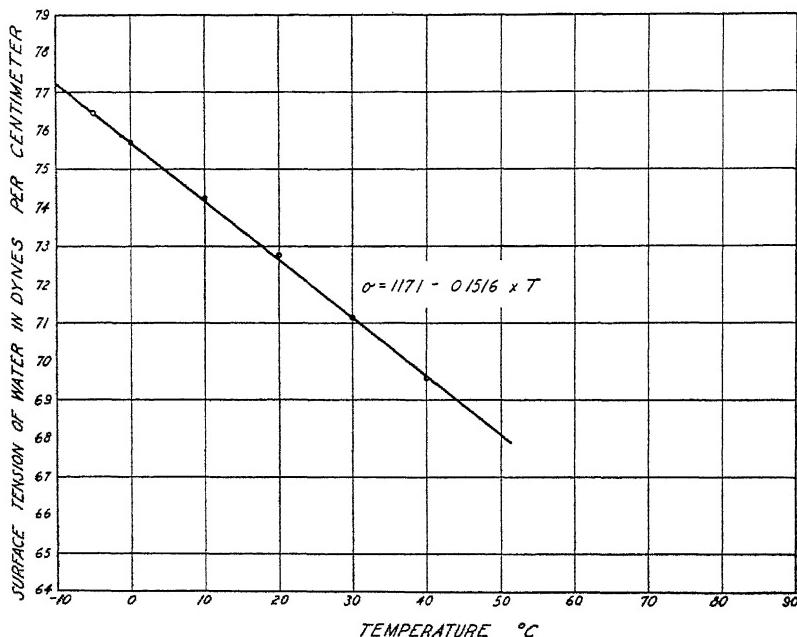


Fig. 42.—Variation of surface tension with temperature.

Similarly by equation 435 one can compute the vapor pressure of a relatively moist soil at any temperature  $T$  if the free energy  $\Delta f_{ST_1}$  or the vapor pressure  $p$  of the moist soil has been determined at some temperature  $T_1$ . This is clear from a further consideration of equation 435.

$$RT \ln \frac{p}{p_0} = \frac{\Delta f_{ST_1}}{\sigma_{T_1}} (117 - 0.152T)$$

or

$$\ln \frac{p}{p_0} = \frac{\Delta f_{ST_1} (117 - 0.152T)}{\sigma_{T_1} RT}$$

so that

$$p = p_0 e^{\left(\frac{\Delta f_{ST_1}}{R\sigma_{T_1}}\right) \left(\frac{117}{T} - 0.152\right)}. \quad (437)$$

According to this equation, if we know  $\Delta f_{ST_1}$  of a relatively moist soil at a particular moisture content and temperature  $T_1$ , we can compute the vapor pressure  $p$  of this same sample of soil at any other temperature  $T$ , where  $p_0$  is the vapor pressure of free, pure water at the temperature  $T$ . All the other quantities such as  $R$  and  $\sigma_T$  can be obtained from a set of physical tables.

Note again that equation 435 holds only for a relatively moist soil where the adsorptive force field surrounding the soil particle is negligible at the air-water interface.

Equation 437 might give the impression that the vapor pressure of soil moisture should decrease with increase of temperature, since the absolute value of the exponent decreases with temperature. It must be recalled (eq. 121), however, that the numerical value of the free energy  $\Delta f_{ST_1}$  has always been found negative for unsaturated soil moisture. Thus the vapor pressure  $p$  will increase with a rise in the soil-moisture temperature  $T$ . Clearly, judging from the form of the equation, as the temperature  $T$  increases, the vapor pressure of the soil moisture  $p$  will approach that of the free water  $p_0$ . As the critical temperature of water is approached, its surface tension approaches zero; and consequently the factor in the exponent of equation 437 reduces to zero at this temperature, making the exponential unity and  $p$  equal to  $p_0$ .

#### 75. Dependence of the Variation in Height of a Water Table on the Variation in Temperature of the Soil Moisture

Equation 436 may be used as the basis to account for the diurnal variation in height of a water table close to the surface of the ground. As all soil workers have observed, a water table close to the surface of the ground gradually rises from dawn till about sunset and then begins to fall, continuing to fall throughout the night. The whole process is repeated the next day. The amplitude of the variation in height of the water table is found to increase with an increase in the amplitude of variation of the soil temperature between the day and the night.

Superimposed upon these fluctuations there will be a gradual and progressive lowering of the water table if the root hairs of actively transpiring vegetation are present and if the water table is close enough to the soil surface to make upward capillary movement appreciable. Sometimes, where the water table is close to the surface and plants are growing, the water table drops during the day because of transpiration. We are here concerned with none of these. What we are interested in is only a fluctuation in the height of the water table, without any total loss (through plants) of water from the whole soil-moisture system composed of the water table plus the overlying moist soil.

To illustrate the application of equation 436 to the explanation of the variation in height of a water table with temperature, let us consider the simplest case of the variation in height of a column of water in a vertical capillary tube dipping into a free water surface. Figure 43 shows a capillary tube of radius  $r$  having its lower end in a vessel of water. At the temperature  $T_1$  the height is  $h_{T_1}$ ; at a higher temperature  $T$ , for example, the column will have dropped to  $h_T$ . For the present we are neglecting the effect of such minor influences as the slight change in the density  $\rho$  of water caused by changes of its temperature.

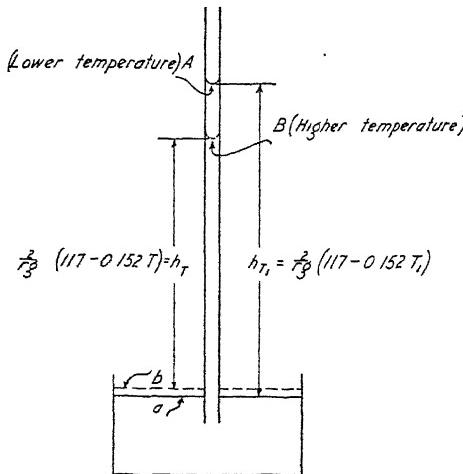


Fig. 43.—Illustration of change in water table with temperature.

If at the temperature  $T_1$  the free energy is  $\Delta f_{T_1}$  just below the meniscus at  $A$ , and if at the temperature  $T$  it is  $\Delta f_T$  just below the new position of the meniscus at  $B$ , we have (eq. 436)

$$\Delta f_T = \frac{\Delta f_{T_1}}{\sigma_{T_1}} (117 - 0.152T). \quad (438)$$

This equation applies to any relatively moist soil, no matter how saline. From equation 211 we have

$$\Delta f_{T_1} = \frac{2\sigma_{T_1} v}{r}. \quad (439)$$

Here, as will be recalled,  $r$  is negative when the vapor-water interface is concave to the vapor phase. Inserting equation 439 into 438,

$$\Delta f_T = \frac{2v}{r} (117 - 0.152T). \quad (440)$$

Let us now express the height of the capillary column  $h$  in terms of the temperature  $T$  of the capillary column. From equation 156 we have, for the free energy due to hydrostatic pressure immediately below the water meniscus,

$$\Delta f_T = v \Delta P. \quad (441)$$

Since  $\Delta P$  immediately below the meniscus equals the weight of the column of water (of length  $h$  and unit cross section) under the meniscus, we have  $\Delta P = -h \rho g$ . We insert the negative sign because  $\Delta P$  here represents a state of tension or negative hydrostatic pressure with respect to our datum. Equation 441 then becomes

$$\Delta f_T = -h \rho g \quad (442)$$

where  $g = 980$  dynes per gram.

Inserting  $\Delta f_T$  of 442 into 440 and solving for  $h$ , we have

$$h = -\frac{2}{gr} (117 - 0.152T), \quad (443)$$

where  $\rho$  and  $v$  have been omitted because the density  $\rho$  and the specific volume  $v$  of water are approximately unity in the c.g.s. system, and where the radius of curvature  $r$  is substituted as a negative value according to our previous convention.

According to equation 443, the height  $h$  of the capillary column rises as the temperature decreases and falls as the temperature rises. Thus, considering figure 43, we find equation 443 predicting that with rise of temperature the water table will rise from  $a$  to  $b$  as the capillary column drops from  $A$  to  $B$ . The amount of the rise  $ab$  of the water table can, of course, easily be calculated from a knowledge of the diameters of the capillary tube and the vessel.

- This case of the simple capillary tube and the variation in height of its water table with changes of temperature is analogous to the actual situation found in a moist soil with a high water table. When equilibrium of the soil moisture has been established at a temperature  $T_1$  in a soil column in contact with a body of water (fig. 44,  $A$ ), the relation between the free energy  $\Delta f_{T_1}$  of the soil moisture at a height  $h$  (on the one hand) and the height  $h$  (on the other) may be schematically represented by the straight line  $\Delta f_T$  of figure 44,  $B$ . This, as well as the following statements, is entirely justified by the next article, which should be read in connection with the present one. Under equilibrium conditions of soil moisture, the

rate of change of the free energy  $\Delta f_{T_1}$  with respect to the height  $h$  (eq. 442) must be equal but opposite in sign to  $g$ , the gravitational force. That is,

$$\frac{d(\Delta f_{T_1})}{dh} = -g, \quad (444)$$

since  $\rho = 1$ . At the water table,  $\Delta f_{T_1} = 0$ , while at the top of the soil column, the free energy of the soil moisture  $\Delta f_{T_1}$  has reached its maximum negative value. The soil moisture contents  $C_{T_1}$  throughout the soil col-

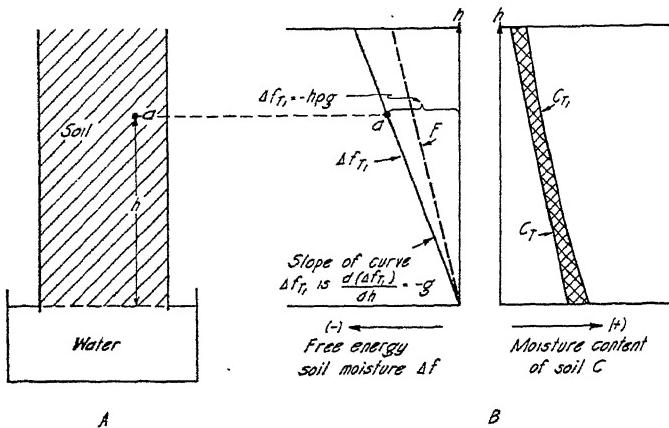


Fig. 44.—Variation of soil moisture with height above a water table because of variation of its free energy with temperature.

umn, corresponding to the free energy  $\Delta f_{T_1}$  at different heights  $h$ , are given by curve  $C_{T_1}$  also placed in figure 44, B. The highest moisture contents are, of course, at the bottom of the soil column.

Suppose we now raise the temperature of the entire soil-moisture system from  $T_1$  to  $T$  and inquire what will happen to the free energy  $\Delta f$  of the soil moisture throughout the soil column, as well as to the moisture content  $C$ . From what has gone before, based upon equations 440 and 443, we should expect the free-energy curve  $\Delta f$  to drop temporarily to some such position as  $F$ . In other words, the free energy  $\Delta f$  of every element of moisture throughout the soil column at different heights  $h$  above the water table will have decreased numerically.

The free energy throughout the soil column cannot remain at equilibrium in the state represented by  $F$ , since under these conditions the gradient of the free energy is not equal to minus  $g$  (eq. 444). This relation represents the rate of change of the free energy in any soil column at any temperature at equilibrium.

Changes will therefore be set up throughout the soil column, no matter what the temperature change happens to have been, tending to restore  $\Delta f$  throughout the soil column to the values represented by curve  $\Delta f_{T_1}$ , so that the gradient of the free energy  $\frac{d(\Delta f)}{dh}$  at the new temperature  $T$  is restored to the same value, minus  $g$ . These readjustments will involve a progressive change of moisture contents throughout the soil column from  $C_{T_1}$  to those represented by the curve  $C_T$  when the temperature is raised. In other words, if the temperature is raised, water will flow out of the soil and into the water table, which will raise the height of the water table. (Likewise if the temperature of the soil column is lowered, water will move into the soil, and the water table will be lowered. The curves corresponding to the lowering of the temperature are not shown in the graph, but would be displaced in the direction opposite to  $C_T$ .) The equilibrium moisture distribution represented by the curve  $C_T$  is such that equations 444 and 442 are satisfied. At equilibrium the free-energy curve  $\Delta f_T$  at the higher temperature  $T$ , corresponding to  $C_T$ , therefore coincides with  $\Delta f_{T_1}$ . The reasons for this fact, besides those already given, follow immediately.

According to equation 442, the free energy  $\Delta f$  of the moisture in a soil column in contact with a water table under equilibrium conditions depends only on its height  $h$  above the water table. No matter what the temperature  $T$  happens to be, the free energy  $\Delta f$  at equilibrium is given by

$$\Delta f = -h \rho g .$$

Any variation of  $\rho$ , the density of water, with changes of temperature is a second-order effect and is therefore negligible. The question then is, how can the soil column at the higher temperature  $T$  maintain the same free energy throughout as represented by the curve  $\Delta f_{T_1}$ , when equation 440 seems to predict that the free energy  $\Delta f_T$  of the soil column will rise (become less negative) with rise in temperature to some such curve as  $F$  in figure 44, B?

This difficulty is immediately cleared up when we recall the following experimental facts: (1) when the temperature is raised, water moves down in the soil and runs out of the bottom of the column, the soil moisture content thus being decreased; (2) as the soil moisture content is decreased, the free energy  $\Delta f$  of soil moisture decreases—becomes more negative.

As the temperature of the soil column is raised, the free-energy curve  $\Delta f_{T_1}$  will therefore temporarily tend to move to the position  $F$ , corresponding to a greater positive free energy at a height  $h$ . While this is going on, however, water will drain out of the bottom of the soil column

into the water table, which will cause the free energy at a given height  $h$  to become more negative and simultaneously counteract the change of  $\Delta f$  caused by the rise of temperature, until finally the free energy represented by curve  $\Delta f_{T_1}$  is reestablished throughout the soil column and the free-energy curve  $\Delta f_T$  at the higher temperature  $T$  coincides in position with  $f_{T_1}$ . The net result of the rise in temperature of the soil column is, then, the downward movement into the water table of the amount of soil moisture represented by the shaded area between the curves  $C_{T_1}$  and  $C_T$ . The water table accordingly rises with a rise in temperature, and no change finally occurs in the free energy  $\Delta f$  throughout the soil column caused by a change in temperature.

The reverse of the results obtained above would, naturally, have occurred if the temperature of the soil column had been lowered.

Carrying the analyses further, we should be able to calculate quantitatively the amount of water that would move into or out of a soil column and into the water table, with changes of temperature, merely by using equations 438 and 442 and by knowing the dependence of the free energy  $\Delta f_T$  of the soil moisture, at but a single temperature  $T$ , on the soil moisture content.

If the soil is relatively dry, equation 438 should be replaced by the more comprehensive equation 477 or 484 and by the treatment of articles 80 and 81.

#### 76. Dependence of the Free Energy on Height $h$ above a Free, Pure Water Surface Used as the Datum

In article 75 (eq. 442) it was shown that the free energy of water just under the meniscus, in a capillary tube (fig. 43), at the height  $h$  above the free water surface is given by

$$\Delta f = -h \rho g$$

where  $\rho$  is the density of water in grams per cc and  $g = 980$  dynes. In this article, we shall show, as a corollary to the previous one, that *under equilibrium conditions* equation 442 gives the free energy  $\Delta f$  of water at a height  $h$  above free, pure water, no matter whether the water at the height  $h$  is in a capillary tube (as in the present case), or is soil moisture in a column of soil at a height  $h$  above the water table, or is vapor at a height  $h$  above a free water surface (art. 37).

The truth of this statement is seen immediately when one considers a soil column and a capillary tube both dipping down into a vessel of free, pure water used as the datum, the whole being contained in a closed chamber such as a large bell jar. When equilibrium has been established,

the liquid and vapor phases will be in equilibrium throughout the whole system, composed of the soil column and capillary tubes, all dipping down into the body of free water, surrounded by water vapor. Thus if the meniscus in the capillary tube comes to equilibrium at the height  $h$ , it will be in equilibrium with the vapor at that level. Likewise the soil moisture at the height  $h$  in the soil column will also be in equilibrium with the vapor at the height  $h$ . If they are not at equilibrium, a readjustment will take place until they are.

We see (art. 22) that the free energy of the water in the soil column, in the capillary tube, and in the vapor phase are the same at the same height  $h$ , when equilibrium has been established. Thus, no matter in what state water happens to be (whether as water in a capillary tube, soil moisture, or vapor) at a height  $h$  above the free water surface (when each of them is in equilibrium with the free water surface used as the datum), the free energy of the water, expressed in terms of that in the capillary at the height  $h$ , is given by  $\Delta f = -h \rho g$ . Expressed in terms of the vapor pressure  $p$  at the height  $h$  above the free water surface, it is (eq. 159 and 236)

$$\Delta f = RT \ln \frac{p}{p_0} \text{ where } p_0 \text{ is the vapor pressure at the free water surface used as the datum.}$$

The equation  $\Delta f = -h \rho g$  presents one method (similar to the one previously used by many soil workers—20, 56, 81—for determining the capillary potential of soil moisture at different soil moisture contents) for determining the free energy of soil moisture at different moisture contents. The soil moisture in a long soil column dipping down into free, pure water is allowed to come to equilibrium throughout with the surface of free, pure water taken as the water table. When equilibrium has been established, the moisture content in the soil column will vary uniformly from saturation, at the lower end next to the free water surface, to relative dryness at the upper end of the soil column. The soil column is then taken down, broken up into small sections, and the moisture contents at the different heights  $h$  determined. The free energy corresponding to each different soil moisture content (associated with a definite value of the height  $h$  above the water table) is computed immediately from  $\Delta f = -h \rho g$ . Thus a curve can be plotted showing the dependence of the free energy  $\Delta f$  of the soil moisture on the moisture content, just as has been done in the past for the capillary potential of soil moisture.

This method of determining the relation between soil moisture content and its free energy, although sound theoretically, is somewhat impractical because years are required for the soil moisture in a soil column to come to complete equilibrium with a water table, and because the temperature of the soil must be maintained constant throughout this time interval.

**77. Dependence of the Free Energy  $\Delta f_s$  of Soil Moisture on Changes in Temperature  
When the Ratio of the Vapor Pressures  $\frac{p}{p_0}$  Remains Constant**

The following treatment will be particularly applicable to very saline moist soils where, as will be shown later (art. 78), the ratio of the vapor pressure  $p$  of the solution to that of pure water  $p_0$  remains practically unchanged with changes of temperature. It will also apply directly to any other cases where future experiments show that the ratio  $\frac{p}{p_0}$  is relatively constant.

We shall proceed immediately to show how  $\Delta f_s$ , at a particular soil moisture content, might be calculated at any desired temperature when  $\Delta f_s$  has been experimentally determined at but one temperature,  $T_1$ . As mentioned before, this calculation has not been possible with the quantities called capillary potential and total potential used in the past for describing the energy relations of soil moisture.

Equation 146, the basis for our development, is

$$\left( \frac{d(\Delta f_s)}{dT} \right)_p = -\Delta s. \quad (445)$$

Before using this expression, let us understand the meanings attached to the symbols  $d$  and  $\Delta$  in our present problem. Figure 45 has been considerably distorted to bring out the meanings of the symbols  $\Delta$  and  $d$  (differential).

To avoid confusion, we must recognize clearly that we are dealing in equation 445 with two types of changes in the value of the absolute free energy  $f$ . One change symbolized by  $\Delta$ , as  $\Delta f$ , indicates the difference between the value of the absolute free energy of the soil moisture and the value of the absolute free energy of pure water in the standard state, both states being considered at the same temperature. A change in  $\Delta f$ , called the free energy of the soil moisture, is produced entirely by a change of soil moisture content, the temperature remaining constant. For example, at *A* in figure 45 this change or difference is represented by  $\Delta f_{ST_1}$ ; at *B* by  $\Delta f_{ST_2}$ . The other change, symbolized by  $d$ , as  $d(\Delta f)$ , arises from a variation of temperature, all other variables such as soil moisture content remaining constant. At the temperature  $T_1$ , for instance, the free energy of the soil moisture is  $\Delta f_{ST_1}$ . If now the temperature is raised by an amount  $dT$ , the free energy  $\Delta f_{ST_1}$  is further increased by an amount  $d(\Delta f_{ST_1})$  so that the free energy of the soil moisture at  $T_2$ ,  $\Delta f_{ST_2}$ , now equals the sum  $\Delta f_{ST_1} + d(\Delta f_{ST_1})$ . The quantity  $\Delta s$  (eq. 445), since it involves the symbol  $\Delta$ , refers to the change in entropy per gram of water in going from the state of pure water  $f_0$  to the soil moisture in the state  $f$ , both states being at the same temperature.

Summarizing, therefore, we can say that according to equation 445, the rate of change,  $\left(\frac{d(\Delta f_s)}{dT}\right)_p$ , of the free energy  $\Delta f_s$  of soil moisture with respect to temperature equals the negative of the specific entropy  $\Delta s$  of the soil moisture, with respect to free, pure water, the soil moisture and free, pure water being at the same temperature when  $\Delta s$  is computed. Clearly, the vapor pressure of soil moisture differs from that of pure water at the same temperature, and the subscript  $p$  indicates that the vapor pressure

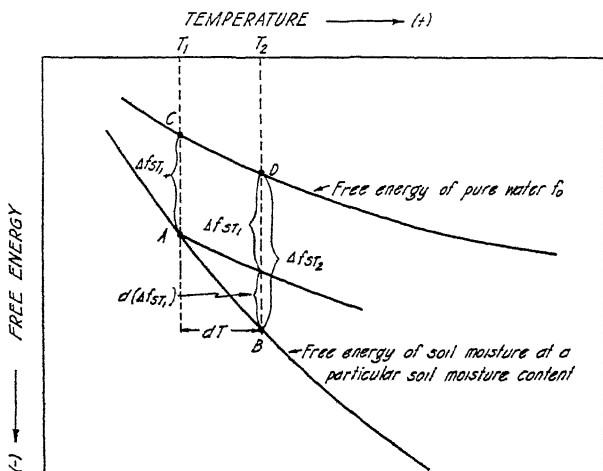


Fig. 45.—Illustration of two different types of changes in free energy of soil moisture at a given moisture content due to change in temperature.

of pure water as well as the vapor pressure of soil moisture must be regarded as constant during variations of temperature.

The evaluation of the free energy  $\Delta f_s$  will be performed in two steps. The first step will consist in an integration of equation 445, which will give the change in free energy  $\Delta f_s'$  in going from one temperature  $T_1$  to another temperature  $T$ , assuming that the vapor pressures do not change with temperature. The latter state, of course, is a hypothetical condition not found in nature. The second step will consist of showing that the difference in free energy between this hypothetical state and that actually experienced in nature is negligible. Thus we shall have determined the actual free energy of the soil moisture at the higher temperature.

To proceed with the first step, let us recall (art. 22) that the free energy is the same in all phases of a given substance when at equilibrium. Consequently, the free energy  $\Delta f_s'$  of the vapor phase always equals the free energy of the liquid phase of the soil moisture. If, therefore, we calculate

the changes in free energy of the vapor phase caused by changing the temperature of the soil moisture, we have also calculated the change in the free energy of the soil moisture. In the present case, as in numerous others, it is much easier (art. 39) to deal with the vapor phase. We shall therefore carry out the following analysis with respect to the vapor phase.

Returning to equation 445 and using the notation  $\Delta f_s$  to represent the free energy of soil moisture, we have

$$d(\Delta f_s') = -\Delta s dT. \quad (446)$$

Integrating between the temperature  $T_1$  and  $T$ ,

$$\Delta f_{ST'} - \Delta f_{ST_1} = - \int_{T_1}^T \Delta s dT. \quad (447)$$

Here  $\Delta f_{ST'}$  represents, as before, the value of the specific free energy of soil moisture in the hypothetical state at any temperature  $T$ , and  $\Delta f_{ST_1}$  that at  $T_1$ , the initial state.

To evaluate the integral, we may conveniently express  $\Delta s$  in terms of variables such as  $p$ ,  $v$ , or  $T$ , which can be measured. From equation 16 we have

$$\Delta s = - \int_{p_{01}}^{p_1} \left( \frac{\partial v}{\partial T} \right)_p dp. \quad (448)$$

Here  $p_{01}$  refers to the vapor pressure of free, pure water at the standard state, and  $p_1$  to the vapor pressure of the soil moisture, both at the same temperature  $T_1$ . To evaluate  $\left( \frac{\partial v}{\partial T} \right)_p$  let us assume that the water vapor surrounding the soil moisture obeys the ideal gas law as stated in equation 367 by

$$v = \frac{RT}{p}.$$

Differentiating  $v$  with respect to  $T$ ,

$$\left( \frac{\partial v}{\partial T} \right)_p = \frac{R}{p}. \quad (449)$$

Thus equation 448 becomes, by substituting from 449,

$$\Delta s = -R \int_{p_{01}}^{p_1} \frac{dp}{p}. \quad (450)$$

Integrating equation 450 to determine the change in entropy of the soil moisture in taking it from the standard state, corresponding to the vapor pressure  $p_{01}$ , to the state corresponding to the vapor pressure  $p_1$ , we have

$$\Delta s = -R \ln \frac{p_1}{p_{01}}. \quad (451)$$

Substituting the value of  $\Delta s$  (eq. 451) into equation 447, we have

$$\Delta f_{ST'} = \Delta f_{ST_1} + R \int_{T_1}^T \ln \frac{p_1}{p_{01}} dT. \quad (452)$$

As will be recalled,  $p_1$  and  $p_{01}$  above refer to the vapor pressure over the moist soil and free, pure water, respectively, at the temperature  $T_1$ , the moisture content of the soil remaining the same throughout the temperature changes involved in the integration above.

Equation 452 is based, of course, on equation 446, in which the vapor pressure of the soil moisture as well as that of the free, pure water was assumed to remain unchanged with changes of temperature. The term  $\Delta f_{ST'}$  of 452 therefore gives the free energy of the soil moisture in the hypothetical state at the temperature  $T$ , under the assumption that the vapor pressures  $p_1$  of soil moisture and  $p_{01}$  of pure water do not change with temperature.

Now, proceeding to the second step, we shall show that the free energy  $\Delta f_{ST'}$  of the soil moisture given by equation 452 in the hypothetical state is practically equal to the free energy  $\Delta f_{ST}$  actually found by experiment at the temperature  $T$ . To do this, let us reduce equation 452. Since the logarithmic term in the hypothetical state is independent of temperature because the vapor pressures  $p_1$  and  $p_{01}$  were assumed to be unchanged in going from  $T_1$  to  $T$ , equation 452 may be placed in the following form:

$$\Delta f_{ST'} = \Delta f_{ST_1} + R \ln \frac{p_1}{p_{01}} \int_{T_1}^T dT. \quad (453)$$

Substituting for the free energy  $\Delta f_{ST_1}$  of soil moisture at the temperature  $T_1$  from equation 236 and integrating, we have

$$\begin{aligned} \Delta f_{ST'} &= RT_1 \ln \frac{p_1}{p_{01}} + R(T - T_1) \ln \frac{p_1}{p_{01}} \\ &= RT \ln \frac{p_1}{p_{01}}. \end{aligned} \quad (454)$$

Here the vapor pressures not only are those found experimentally for the

soil moisture at the initial temperature  $T_1$  but are also those of the hypothetical state, since we assumed the vapor pressures to be unchanged by temperature in going to the hypothetical state. Since the vapor pressures were assumed to be constant in the derivation of equation 454, then the ratio  $\frac{p_1}{p_{01}}$  is also independent of temperature and is the same at the temperature  $T$  (eq. 454) as at  $T_1$ .

According to an experimental fact (as is shown in the next article), the ratio of the vapor pressure of a solution to that of free, pure water is practically independent of temperature, although the vapor pressures themselves change quite markedly with temperature. Thus the ratio of the vapor pressures  $\frac{p}{p_0}$  actually found experimentally at the temperature  $T$  will prove experimentally to be the same as the ratio  $\frac{p_1}{p_{01}}$  of the hypothetical vapor pressures at  $T$ . The pressures  $p_1$  and  $p_{01}$  are, of course, the actual pressures found at the temperature  $T_1$ . Since the free energy of the solvent of a solution depends only on the ratio of the vapor pressures (eq. 227), we may write, for the true experimental value of the free energy  $\Delta f_{ST}$  of the soil moisture at the temperature  $T$ ,

$$\Delta f_{ST} = RT \ln \frac{p}{p_0}. \quad (455)$$

Obviously, the right-hand side of equation 454, giving the free energy  $\Delta f_{ST}'$  of the soil moisture in the hypothetical state to the temperature  $T$ , is equal numerically to the right-hand side of equation 455, giving the actual free energy  $\Delta f_{ST}$  of the soil moisture in the real state at the temperature  $T$ , since the two vapor-pressure ratios  $\left(\frac{p_1}{p_{01}}\right)$  at the temperature  $T_1$

and  $\left(\frac{p}{p_0}\right)$  at the temperature  $T$ ) were originally assumed to be the same.

Thus we have shown that the actual free energy  $\Delta f_{ST}$  of soil moisture at the temperature  $T$  is equal numerically to the free energy  $\Delta f_{ST}'$  of the hypothetical state and is given by equation 453 or 454. We then have

$$\Delta f_{ST} = \Delta f_{ST_1} + R(T - T_1) \ln \frac{p}{p_0}, \quad (456)$$

where the pressures  $p$  and  $p_0$  are those at any temperature between  $T$  and  $T_1$ , since the ratio is independent of temperature.

Thus, knowing the free energy of the soil moisture of a very saline moist soil at but one temperature  $T_1$ , we can immediately by equation 456 calculate the free energy  $\Delta f_{ST}$  of the soil moisture at any other temperature  $T$ .

78. Dependence of the Free Energy  $\Delta f_{ST}$  on the Temperature, the Presence of Dissolved Material Only Being Considered

The treatment in the present article, using the results of the previous article, applies particularly to a very saline moist soil, and possibly to other cases in soils if future experimental work shows the ratio of the vapor pressures  $\frac{p}{p_0}$  to be independent of changes in temperature. Let us examine whether experimental evidence now available will support our

TABLE 1  
DEPENDENCE OF VAPOR PRESSURE OF SOLUTION ON TEMPERATURE

Temperature	Vapor pressure			Ratio, $\frac{p}{p_0}$	
	Of $H_2O$ , $p_0$	Of 2.5 per cent solution of $NaCl$ , $p_{NaCl}$	Of 5.0 per cent solution of $Na_2CO_3$ , $p_{Na_2CO_3}$	$\frac{p_{NaCl}}{p_0}$	$\frac{p_{Na_2CO_3}}{p_0}$
$^{\circ}C$	mm	mm	mm	ratio	ratio
0 . . . . .	4 58	4 5	4.5	0 982	0 982
10. . . . .	9 21	9 1	9 0	989	978
20 . . . . .	17 5	17 3	17.2	989	983
30 . . . . .	31 8	31 4	31 2	987	981
40 . . . . .	55 3	54 5	54 2	986	980
50. . . . .	92 5	91 2	90 7	986	981
60 . . . . .	149 3	147 2	146 5	0 986	0 981

assumption that the ratio  $\frac{p}{p_0}$  is independent of temperature for a saline solution.

Table 1, taken from the *International Critical Tables*, gives the aqueous vapor pressures of pure water, of sodium chloride solution, and of sodium carbonate solution at different temperatures. From the vapor pressures, the last two columns have been computed. Evidently, the ratio of the vapor pressure  $p$  over the solution to that over the free, pure water surface  $p_0$  is essentially independent of temperature over the temperature range considered. We should also note that the two solutions taken represent more extreme conditions, with respect to vapor-pressure depression caused by dissolved material, than are customarily found in soils.

Having shown above that  $\ln \frac{p}{p_0}$  remains approximately constant as the temperature  $T$  of the solution is changed, we are justified in using equation 456 in calculating the dependence of the free energy  $\Delta f_{ST}$  on temperature:

$$\Delta f_{ST} = \Delta f_{ST_1} + R(T - T_1) \ln \frac{p}{p_0}. \quad (457)$$

Figure 46 should clarify the meaning of equation 457, which gives the free energy  $\Delta f_{ST}$  of a sample of soil moisture at any temperature  $T$  in terms of a known value of the free energy  $\Delta f_{ST_1}$ . Since the ratio  $\frac{p}{p_0}$  is independent of temperature, it can be expressed in terms of  $\Delta f_{ST_1}$ . Figure 46 shows that in taking the sample of moist soil from the temperature  $T_1$  at which we know the free energy  $\Delta f_{ST_1}$  and the vapor pressure  $p$ , to any other temperature  $T$ , the free energy of the soil moisture changes to  $\Delta f_{ST}$  (eq. 457). This relation enables one to calculate  $\Delta f_{ST}$  at any tem-

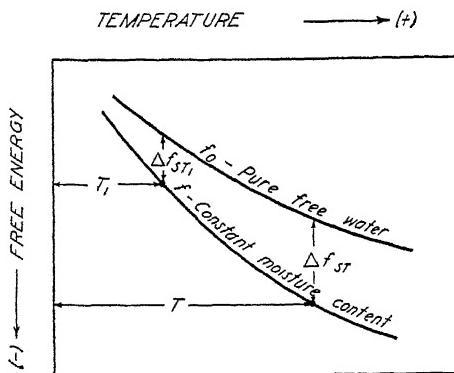


Fig. 46.—Change of free energy of soil moisture with temperature at a given moisture content.

perature  $T$  for a particular moisture content provided  $\Delta f_{ST}$  is known at some one temperature.

A more useful expression can be obtained if we further transform equation 457. As will be recalled (art. 39), the free energy of soil moisture  $\Delta f_{ST_1}$  may be expressed in terms of the vapor pressure of the soil moisture as follows:

$$\Delta f_{ST_1} = RT_1 \ln \frac{p}{p_0}. \quad (458)$$

Introducing 458 into equation 457, we have

$$\Delta f_{ST} = RT_1 \ln \frac{p}{p_0} + R(T - T_1) \ln \frac{p}{p_0}. \quad (459)$$

Expanding the last member of this equation and cancelling out like terms, we have

$$\Delta f_{ST} = RT \ln \frac{p}{p_0}. \quad (460)$$

To transform this equation into a more useful form, let us multiply the numerator and denominator of the right-hand side by  $T_1$ , the temperature corresponding to the known value of the free energy  $\Delta f_{ST_1}$ , and recall 458. Equation 460 becomes

$$\Delta f_{ST} = \frac{T}{T_1} \Delta f_{ST_1}. \quad (461)$$

If we know, therefore, the free energy  $\Delta f_{ST_1}$  of the soil moisture of a saline soil at any particular moisture content and temperature  $T_1$ , we may readily calculate the free energy  $\Delta f_{ST}$  at some other temperature  $T$ , but at the same moisture content. This equation may be applied to any soil moisture whose free energy is due mainly to the presence of dissolved material.

Thus one can calculate the free energies  $\Delta f_{ST}$  for a series of moisture contents at any temperature  $T$  if the free energies  $\Delta f_{ST_1}$ , at some one temperature  $T_1$ , are known for the same series of moisture contents. Equation 461 shows, for a very saline soil, that the free energy  $\Delta f_{ST}$  of soil moisture decreases as the temperature of the moist soil is raised.

Equation 461 may be derived with much less effort by another method if we recall the experimental observation, from table 1, that the ratio of the vapor pressure  $p$  of a solution to that of pure water  $p_0$  at a given temperature is a constant independent of temperature over the range of concentrations shown.

The free energy  $\Delta f_{OT}$  of a solution due to osmotic pressure has been defined (eq. 227) by

$$\Delta f_{OT} = RT \ln \frac{p}{p_0}. \quad (462)$$

When applied to solutions,  $\Delta f_{OT}$  has the same significance that  $\Delta f_{ST}$  does when applied to very moist saline soils. We may therefore write this equation in the following form for our present use:

$$\Delta f_{ST} = RT \ln \frac{p}{p_0}. \quad (463)$$

Let us assume that  $\Delta f_{ST}$  has been determined at some particular temperature  $T_1$  and found to be

$$\Delta f_{ST_1} = RT_1 \ln \frac{p}{p_0}. \quad (464)$$

Dividing equation 463 by 464 and recalling the constancy of the ratio

$\frac{p}{p_0}$  of the vapor pressure of a solution to that of free water despite variations of temperature, we have

$$\frac{\Delta f_{ST}}{\Delta f_{ST_1}} = \frac{T}{T_1}$$

or

$$\Delta f_{ST} = \frac{T}{T_1} \Delta f_{ST_1}, \quad (465)$$

which is the same as equation 461.

#### 79. Dependence of the Free Energy $\Delta f_{ST}$ of Soil Moisture on the Temperature, the Effect of the Adsorptive Field Only Being Considered

The dependence of the free energy on the adsorptive field alone probably corresponds to no actual condition found with soil moisture. It approximates most closely the conditions to be expected in a relatively dry soil if very little dissolved material were present in the soil moisture. As the moisture film surrounding the soil particles becomes thinner, the air-water interface of the film comes increasingly under the influence of the adsorptive force surrounding the soil particles. The chief reason for introducing a treatment of this case is to complete the basic considerations necessary for the treatment of the generalized case to follow, which considers all the principal factors contributing to the free energy  $\Delta f_{ST}$  of soil moisture.

The free energy  $\Delta f_{ST}$  is given, as before, by

$$\Delta f_{ST} = RT \ln \frac{p}{p_0}.$$

It is a well-known fact that the electrostatic field surrounding a charged particle is not appreciably affected by temperature changes. Since the adsorptive field surrounding the soil particles arises from the unsatisfied electrostatic forces of the surface molecules of the soil particles, we shall assume, to a first approximation, that the adsorptive field as well as its resultant effects are not much modified by changes of temperature. The quantity of water adsorbed on soils of course decreases with increase in temperature; but this decrease occurs because the kinetic energy of the adsorbed molecules is higher at the higher temperatures rather than because the field changes with temperature. The sum, therefore, of the component of the free energy of water  $\Delta f_{FS}$  due to its presence within the adsorptive field surrounding the soil particle, as well as the component of the free energy of the moisture due to the hydrostatic pressure  $\Delta f_P$  caused by the pull of the adsorptive force on the superincumbent layer of

moisture (art. 64), is a constant  $K$  with respect to changes of temperature. That is,

$$\Delta f_{ST} = \Delta f_{FS} + \Delta f_{PS} = K. \quad (466)$$

Thus in the next article we shall consider the total change in the free energy ( $\Delta f_{FS} + \Delta f_{PS}$ ) of soil moisture, caused by the presence of the adsorptive field, to be independent of temperature so long as the soil moisture content remains constant throughout the temperature change. Although not considered in the discussion above, the free energy  $\Delta f_{PS}$  due to hydrostatic pressure clearly may be due in part to pressure transmitted from external sources such as atmospheric pressure. Any external pressure not influenced by temperature changes will, of course, be merely superimposed upon  $\Delta f_{PS}$  above; and the form of equation 466 will remain unchanged.

#### 80. Dependence of the Free Energy $\Delta f_{ST}$ of Soil Moisture on Its Temperature $T$ , All Known Factors Affecting the Free Energy of Soil Moisture Being Considered

Having just taken up separately for extreme cases the various factors affecting the free energy  $\Delta f_{ST}$  of soil moisture as the temperature is changed, let us now consider the most general case, where all these factors enter simultaneously.

In the present instance, four component free energies will go to make up the total value of the free energy  $\Delta f_{ST}$  of soil moisture,

$$\Delta f_{ST} = RT \ln \frac{p}{p_0} = \Delta f_{\sigma S} + \Delta f_{PS} + \Delta f_{OS} + \Delta f_{FS}. \quad (467)$$

As before,  $\Delta f_{\sigma S}$  denotes the component of the free energy due to surface tension and radius of curvature of the water-air interface;  $\Delta f_{PS}$ , that due to the hydrostatic pressure of the moisture adjacent to the soil-particle surface caused by the adsorptive forces surrounding the soil particle (but excluding that due to the surface tension and radius of curvature of the water-air interface), as well as due to any pressure transmitted from external sources;  $\Delta f_{OS}$ , that due to the osmotic pressure of the dissolved material; and  $\Delta f_{FS}$ , the free energy possessed by water by virtue of its position in the adsorptive field surrounding the soil particle as well as in the earth's gravitational field. The present generalized treatment is unlike the previous special cases where we had to determine  $\Delta f_{ST}$  experimentally at but a single temperature in order to calculate  $\Delta f_{ST}$  at any other; we must here experimentally determine  $\Delta f_{ST}$  at two temperatures.

Before evaluating  $\Delta f_{ST}$  we must properly express each of the four component free energies in terms of temperature.

Consider first the evaluation of  $\Delta f_{\sigma S}$  as a function of temperature. According to equations 211 and 434,

$$\Delta f_{\sigma S} = 2(117 - 0.152T) \frac{v}{r}. \quad (468)$$

Equation 468 can be placed in the following form, where  $k_1$  and  $k_2$  are constants independent of temperature:

$$\Delta f_{\sigma S} = k_1 + k_2 T. \quad (469)$$

Next let us evaluate  $\Delta f_{oS}$  as a function of temperature. It was previously shown that the ratio of the vapor pressure  $p$  of a solution to that of pure water  $p_0$  at a given temperature is a constant, independent of temperature. Therefore if  $k_3$  is such a constant that

$$R \ln \frac{p}{p_0} = k_3, \quad (470)$$

we have

$$\Delta f_{oS} = RT \ln \frac{p}{p_0} = k_3 T. \quad (471)$$

Finally, as was brought out in the preceding article, the two component free energies  $\Delta f_{FS}$  and  $\Delta f_{PS}$  arising from the existence of the adsorptive field surrounding the soil particle are constants independent of temperature. Therefore we have

$$\Delta f_{FS} + \Delta f_{PS} = k_4, \quad (472)$$

$k_4$  being another constant independent of temperature.

We can now determine in a generalized way the total free energy  $\Delta f_{ST}$  of a moist soil at any temperature, the soil moisture content remaining constant. Substituting equations 469, 471, and 472 into 467, we have

$$\Delta f_{ST} = k_1 + k_2 T + k_3 T + k_4; \quad (473)$$

and upon further combining the terms on the right side, we may write

$$\Delta f_{ST} = C_1 + C_2 T, \quad (474)$$

where  $C_1$  and  $C_2$  are still other constants independent of  $T$ .

Since equation 474 contains two unknowns,  $C_1$  and  $C_2$ , we must determine  $\Delta f_{ST}$  experimentally at any two different temperatures  $T_1$  and  $T_2$  before we can calculate  $C_1$  and  $C_2$  and consequently before calculating

$\Delta f_{ST}$  at any desired temperature  $T$ . Let us assume that  $\Delta f_{ST}$  has been determined experimentally and found to be  $\Delta f_{ST_1}$  at the temperature  $T_1$  and  $\Delta f_{ST_2}$  at the temperature  $T_2$ . We then have

$$\Delta f_{ST_1} = C_1 + C_2 T_1$$

and

$$\Delta f_{ST_2} = C_1 + C_2 T_2.$$

The unknowns  $C_1$  and  $C_2$  are determined immediately if we solve the set of linear simultaneous equations above, with two unknowns, for  $C_1$  and  $C_2$ . We then have

$$C_1 = \frac{T_1 \Delta f_{ST_2} - T_2 \Delta f_{ST_1}}{T_1 - T_2} \quad (475)$$

and

$$C_2 = \frac{\Delta f_{ST_1} - \Delta f_{ST_2}}{T_1 - T_2}. \quad (476)$$

Inserting  $C_1$  and  $C_2$  of equations 475 and 476 into equation 474, we have the free energy  $\Delta f_{ST}$  of soil moisture at any temperature  $T$  in terms of its value at but two temperatures,  $T_1$  and  $T_2$ . Then

$$\Delta f_{ST} = \left( \frac{T_1 \Delta f_{ST_2} - T_2 \Delta f_{ST_1}}{T_1 - T_2} \right) + \left( \frac{\Delta f_{ST_1} - \Delta f_{ST_2}}{T_1 - T_2} \right) T. \quad (477)$$

This equation is the result of the most general treatment in which all the factors known at present (for example, surface tension, osmotic pressure, hydrostatic pressure, and the adsorptive forces surrounding the soil particle) are considered.

Equation 477 in contrast to equations 436, 465, and 466 requires a determination of  $\Delta f_{ST}$  at two temperatures,  $T_1$  and  $T_2$ .

When, therefore, the conditions of the soil moisture happen to agree approximately with those conditions assumed in deriving the simpler equations 436, 465, or 466, it is advisable to use them. Equation 477 is a general one applicable under all conditions of soil moisture, of which 436, 465, and 466 are merely special cases.

To fix our ideas as to the use of equation 477, let us assume the following set of data: At the temperature  $T_1 = 280^\circ A$ ,  $\Delta f_{ST_1}$  of a moist soil at a particular soil moisture content was found equal to  $-3 \times 10^7$  ergs per gram; at  $T_2 = 300^\circ K$ , for the same soil moisture content,  $\Delta f_{ST_2} = -2 \times 10^7$  ergs per gram. Therefore

$$\begin{aligned} \Delta f_{ST} &= \frac{280 \times (-2 \times 10^7) - 300(-3 \times 10^7)}{280 - 300} + \frac{(-3 \times 10^7) - (-2 \times 10^7)}{280 - 300} \times T \\ &= -17 \times 10^7 + 5 \times 10^6 \times T. \end{aligned} \quad (478)$$

Let us now, by equation 478, calculate the free energy  $\Delta f_{ST}$  of our sample of soil moisture at 273° A.

$$\Delta f_{S\ 273} = -17 \times 10^7 + 5 \times 10^6 \times 273 = -3.35 \times 10^7 \text{ ergs per gram.}$$

### 81. Dependence of the Free Energy of Soil Moisture on Temperature, Expressed in Terms of the Differential Heat of Wetting

We shall approach the subject of the variation of the free energy of soil moisture with temperature by a method somewhat less empirical than that used in the previous article. We may, for example, wish to know the free energy  $\Delta f_{ST}$  of soil moisture at some temperature  $T$  but instead find it more convenient to measure its heat of wetting, from which the free energy  $\Delta f_{ST}$  may be computed. The following discussion will show how the free energy  $\Delta f_{ST}$  may be calculated from experimental results on the differential heat of wetting.

We have seen from equation 404 that

$$\left( \frac{\partial q}{\partial m} \right)_T = \frac{RT^2 d \ln \left( \frac{p_0}{p} \right)}{dT} \quad (479)$$

and from equation 236 that a change in the free energy  $\Delta f_{ST}$  in going from free water at a vapor pressure  $p_0$  to the soil moisture at the vapor pressure  $p$  may be expressed by

$$\Delta f_{ST} = RT \ln \left( \frac{p}{p_0} \right)$$

or

$$\frac{\Delta f_{ST}}{RT} = -\ln \frac{p_0}{p}. \quad (480)$$

Substituting equation 480 into 479, we have

$$\left( \frac{\partial q}{\partial m} \right)_T = - \frac{RT^2 d \left( \frac{\Delta f_{ST}}{RT} \right)}{dT}$$

or

$$d \left( \frac{\Delta f_{ST}}{T} \right) = - \left( \frac{\partial q}{\partial m} \right)_T \frac{dT}{T^2}. \quad (481)$$

The value of  $\left( \frac{\partial q}{\partial m} \right)_T$  depends, in general, on the temperature and moisture content. Suppose, now, we keep the moisture content of the material constant and determine experimentally the differential heat of wetting

of the material  $\left(\frac{\partial q}{\partial m}\right)_T$  as some function  $\Phi(T)$  of the temperature  $T$ , enabling us to write the identity

$$\left(\frac{\partial q}{\partial m}\right)_T \equiv \Phi(T). \quad (482)$$

If this function is substituted in equation 481, we have

$$d\left(\frac{\Delta f_{ST}}{T}\right) = -\Phi(T) \frac{dT}{T^2}.$$

Then, integrating between any two temperatures  $T_1$  and  $T$ , we have

$$\int_{T_1}^T d\left(\frac{\Delta f_{ST}}{T}\right) = -\int_{T_1}^T \Phi(T) \frac{dT}{T^2}$$

or

$$\frac{\Delta f_{ST}}{T} - \frac{\Delta f_{ST_1}}{T_1} = -\int_{T_1}^T \Phi(T) \frac{dT}{T^2}. \quad (483)$$

Here  $\Delta f_{ST}$  and  $\Delta f_{ST_1}$  correspond to the free energy of the soil moisture with respect to that of free water at the temperatures  $T$  and  $T_1$ , respectively. Rearranging equation 483, we have

$$\Delta f_{ST} = -T \int_{T_1}^T \Phi(T) \frac{dT}{T^2} + \left(\frac{\Delta f_{ST_1}}{T_1}\right) T. \quad (484)$$

This equation furnishes a rigorous method in addition to those given in articles 74, 78, 79, and 80 for determining the free energy  $\Delta f_{ST}$  of soil moisture as a function of the temperature  $T$ , regardless of whether the differential heat of wetting is due to solution effects or to adsorption of moisture. It requires an experimental determination of the differential heat of wetting  $\Phi(T)$  of the soil sample as a function of temperature between  $T_1$  and  $T$ , as well as a single determination of the free energy  $\Delta f_{ST_1}$  of the soil sample at some one temperature  $T_1$ . Although we may not be able to make all the determinations on only one soil sample, we can make the determinations on different samples, all at the same moisture content.

As equation 484 shows, we can determine the free energy  $\Delta f_{ST}$  of soil moisture at any temperature  $T$  from the differential heat of wetting  $\left(\frac{\partial q}{\partial m}\right)_T$  or, what is the same thing,  $\Phi T$  (eq. 482), provided we know the free energy  $\Delta f_{ST_1}$  at some one temperature  $T_1$ . Equation 484 is most useful in determining the dependence of the free energy of soil moisture on variations of temperature for comparatively dry soils where the

differential heat of wetting  $\left(\frac{\partial q}{\partial m}\right)_T$  is appreciable. Because of the very minute heats of wetting of relatively moist soils, we cannot, with the present development of calorimetric technique, secure dependable results with this equation at high soil moisture contents. More usable approaches at such contents are discussed in articles 74, 77, and 80.

In contrast to the previous methods of determining the dependence of the free energy of soil moisture on temperature, where we considered the various mechanisms involved such as surface tension and salt concentration, equation 484 does not necessitate the assumption of specific mechanisms. Only measurable thermodynamic quantities such as differential heat of wetting and temperature are involved explicitly.

## MOVEMENT OF SOIL MOISTURE

### 82. Importance of Free Energy $\Delta f_s$ in Studies of the Movement and the Equilibrium of Soil Moisture

Because of the thermodynamic properties of the free energy  $\Delta f_s$ , two bodies of moist soil,  $A$  and  $B$ , at the same temperature will be in equilibrium if their values of  $\Delta f_s$  are the same (art. 21 and 22). The *temperature*, as well as the free energies, at  $A$  and  $B$  must be the same if equilibrium is to exist; for the free energies may well be the same at the two points  $A$  and  $B$ , since we may have

$$\Delta f_s = RT_A \ln \frac{p_A}{p_{OA}} = R T_B \ln \frac{p_B}{p_{OB}},$$

and yet equilibrium will not exist if the temperatures are different. If, however,  $\Delta f_s$  of  $B$  is less than that of  $A$ , there will (eq. 115) be a tendency for moisture to move from  $A$  to  $B$  because moisture will always move from points of higher  $\Delta f_s$  to points of lower  $\Delta f_s$ . It will continue to move until the final value of  $\Delta f_s$  at  $A$  is the same as the final value at  $B$ . The value of the free energy at  $A$  will then have decreased, whereas that at  $B$  will have increased. Incidentally, when equilibrium has thus been established, there will have been a net decrease of the total free energy of the system (art. 21).

The different values of  $\Delta f_s$  for different interconnected regions of moisture all tend to approach the same value. If the interconnections are through the vapor rather than the liquid phase, selective distillation will continue until enough moisture has moved from regions of high  $\Delta f_s$  to regions of low  $\Delta f_s$  to make the value of  $\Delta f_s$  uniform throughout. No matter whether the water is liquid, ice, or vapor, moisture will always move from regions of high  $\Delta f_s$  to regions of low  $\Delta f_s$  until the value of  $\Delta f_s$  is uniform throughout.

In perfect analogy with the idea of potential as used in electricity, magnetism, or soil-moisture studies, the gradient of the total specific free energy  $\Delta f_s$  in the soil is the negative of the force per gram acting on the water particle. Also the component of the force acting on a water particle per gram in any direction is the negative of the derivative of the total potential in that direction. All the vector properties usually associated with the gradient of a potential should be associated with the gradient of the free energy  $\Delta f_s$ .

We often hear that the gradient of the capillary or pressure potential at some point equals the negative of the resultant force per gram acting on the water at that point. This statement is not always true. The pressure or capillary potential, as customarily used in the past, seems not to con-

sider the effect of the variation in concentration of dissolved material in producing water movement. The capillary or pressure potential explicitly deals only with the energy in the soil moisture arising from the mechanical tension or pressure existing in the soil moisture.

The free energy  $\Delta f_s$  is a more generalized quantity than any of the others previously used for describing the energy content of water and includes them as special cases only. The free energy  $\Delta f_s$  (art. 60) includes the energy due to the adsorptive field surrounding the soil particle and that due to dissolved material, as well as that due to hydrostatic pressure. It includes any other terms that might be appreciable under certain conditions, such as the kinetic energy of water (taken up at the end of this article) and the energy due to the possible orientation of the water molecules in the vicinity of the water-soil interface. In the present treatment the latter contributions to the free energy  $\Delta f_s$  have been regarded as negligible.

It is self-evident that the adsorptive field surrounding the soil particle can cause differences in hydrostatic pressure and hence in moisture movement. On the other hand, let us show in a preliminary way that dissolved material will also cause movement. Referring to article 40, we see that if a solution is placed in contact through a semipermeable membrane with pure water in a capillary tube, water will, in general, move either into or out of the capillary tube. Let us gradually increase the tension on the pure water in the capillary tube. Water will flow into the solution until the hydrostatic tension  $-\Delta P_P$  in the pure water of the capillary tube numerically equals the osmotic pressure  $\Delta P_o$  of the solution. In other words (art. 24 and 40) when the free energy  $v(-\Delta P_P)$  due to hydrostatic pressure on one side of the semipermeable membrane equals the free energy  $-v\Delta P_o$  due to osmotic pressure on the other side of the membrane, no further movement takes place. If the tension  $-\Delta P_P$  on the pure water is increased until its magnitude is numerically greater than the osmotic pressure  $\Delta P_o$ , water will move from the solution into the pure water in the capillary tube. Thus we see that pure hydrostatic pressure or tension may not be the only cause of capillary movement of soil moisture.

Let us consider the two following hypothetical cases in soils in order to bring out the generalized usefulness of the free energy  $\Delta f_s$  in predicting, under given conditions, the tendency of moisture to move in a soil as well as to show that the capillary, or pressure, potential alone does not determine the movement of moisture in the soil.

Case I (fig. 47) represents a soil column whose capillary or pressure potential (equivalent throughout to  $\Delta f_P$ ) is uniform throughout. In other words, the tension in the moisture, as measured by a porous bulb atmometer immersed in the soil for a long period until equilibrium has been

established, is the same throughout. This involves the assumption that the solution has the same concentration inside the porous bulb as in the soil moisture immediately outside the bulb. That is, the capillary potential at *A* equals that at *B*. A gradual increase of salinity occurs, however,

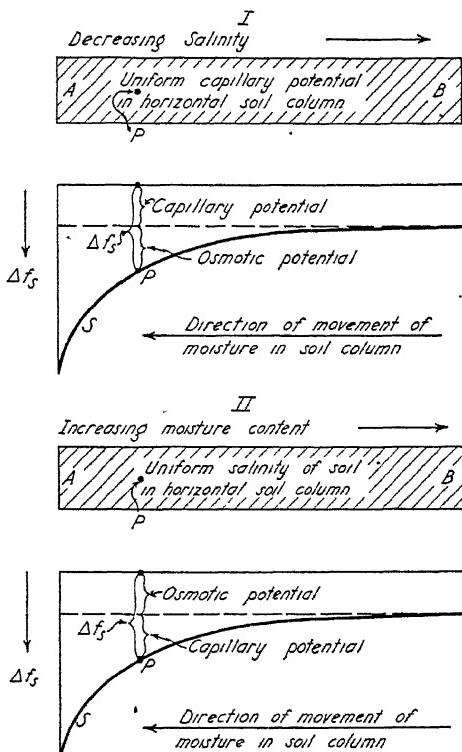


Fig. 47.—A given free-energy gradient produced (I) by varying salinity and uniform capillary potential, and (II) by uniform salinity and varying capillary potential.

in going along the soil column from *B* to *A*. This gives rise to a gradient of the osmotic potential (equivalent to the gradient of  $\Delta f_o$ ) and consequently of the free energy  $\Delta f_s$  of the soil moisture. The gradient or force per gram acting on soil moisture at some point *P* and tending to cause movement in the direction *A* is given by the slope of the curve *S* at the point *P*. There is, in other words, a uniform tendency of moisture to move in the direction from *B* to *A*, although the capillary or pressure potential is the same throughout.

Case II somewhat resembles case I in that the free energy  $\Delta f_s$  at cor-

responding points in the two soil columns have the same values as shown by the graphs. In case II, however, the salinity or osmotic potential (equivalent throughout to  $\Delta f_o$ ) is uniform throughout the soil column; but the soil moisture content is so adjusted along the soil column that the capillary or pressure potential will vary in such a way that corresponding points in the two soil columns have the same value for the total free energy  $\Delta f_s$ . The gradient of the free energy and, in consequence, the force acting on the soil moisture is the same at corresponding points in the two cases. The tendency of soil moisture to move from *B* to *A* in case I is therefore the same as in case II even though the factors giving rise to the movement are entirely different. It does not follow, of course, that the flow density will be the same in the two cases since the moisture contents are not the same.

To be sure, the variation in salinity in the soil column of case I will eventually decrease to zero, while the salt concentration will become uniform throughout by diffusion. No tendency towards movement of moisture will then exist. These considerations lead one to conclude that the porous bulb as generally used for measuring the capillary or pressure potential of soil moisture does not measure the capillary potential, the total potential, or the free energy. It would measure capillary potential only when sufficient time had elapsed to obtain equality in concentration of dissolved material between the soil solution and the water inside the atmometer. It would measure total potential or free energy only if one could get an equilibrium reading before any dissolved salts of the soil solution had moved into the inside of the atmometer. This is impossible because considerable time is required for pressure equilibrium to be established. In practice the porous-bulb technique usually gives a value somewhere between the capillary potential and the total potential, or free energy. For most soils, which are not very saline, this measured value is probably not far from the capillary potential, or the total potential, or the total free energy.

If we are to determine the total energy required to remove water from soil as well as its tendency to move from one point to another, we should, it seems, determine the total free energy  $\Delta f_s$ . The error caused by the diffusion of soil solutes made in measurements of the capillary or pressure potential by the porous-bulb technique will of course depend upon the circumstances, and in some cases will be negligible.

In the discussion above, we have considered the effect of dissolved substances on the osmotic pressure only, and therefore on the free energy  $\Delta f_o$ . Dissolved material affects  $\Delta f_s$  in still another way in that it changes the surface tension of water. Practically all salts cause a slight increase, and many organic substances a considerable decrease, of surface tension.

Such changes of the surface tension will affect the component of the free energy due to hydrostatic pressure. Since the salts as found in soil solutions change the surface tension by a very small percentage, the effect of changes in surface tension caused by dissolved material has been neglected in the foregoing treatment.

As mentioned above, the total free energy  $\Delta f_s$  plays, in a more comprehensive way, the same role in soil-moisture movement as has the potential in many former treatments of the subject (20, 30, 45, 55, 57, 58, 59, 81, 111, 125, 126). It is worth while, therefore, at this point, to restate some of the hydrodynamic equations of soil moisture in terms of free energy  $\Delta f_s$ . In such slow motion as that of water in soils, there is considerable evidence to justify the assumption that the frictional forces are proportional to the velocity. This may be expressed mathematically by

$$V = KF, \quad (485)$$

where  $V$  represents the mean velocity of the soil moisture;  $K$  the proportionality factor, whose magnitude depends on the frictional forces set up by the soil; and  $F$  the driving force on the moisture per unit mass of moisture.

Since, as pointed out earlier in this article, the force  $F$  equals the negative of the gradient of the free energy  $\Delta f_s$ , we may write (eq. 467)

$$F = -\nabla(\Delta f_s) = -\nabla(\Delta f_{\sigma s} + \Delta f_{PS} + \Delta f_{os} + \Delta f_{FS}), \quad (486)$$

where

$$\nabla = i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y} + k \frac{\partial}{\partial z}, \quad \checkmark$$

$i$ ,  $j$ , and  $k$  being unit vectors in the positive direction of the  $x$ ,  $y$ , and  $z$  axes. Here the component free energies have the same meaning as in equation 467.

- Substituting  $F$  from equation 486 into 485, we have

$$V = -K\nabla(\Delta f_s) = -K\nabla(\Delta f_{\sigma s} + \Delta f_{PS} + \Delta f_{os} + \Delta f_{FS}). \quad (487)$$

The factor  $K$  may be regarded as a transmission function. Equation 487 is simply Darcy's law and states that the force acting on soil moisture and, consequently, the velocity of movement of the soil moisture at a given point are proportional (at a given moisture content) to the greatest space rate of change of the four component free energies and have a direction proportional to the greatest space rate of change of the four component free energies.

Now the equation of continuity, which is simply a statement of the law of conservation of mass, is

$$\frac{\partial \rho}{\partial t} = \nabla \cdot (\rho V), \quad (488)$$

where the dot indicates the scalar product of the vector operator  $\nabla$  and the vector  $(\rho V)$  and where  $\rho$  is the moisture density in grams per cubic centimeter at any point in the soil. Since we wish to express at any point the rate of change of the moisture density with time  $\frac{\partial \rho}{\partial t}$ , in terms of the free energy at that point, let us substitute equation 487 into 488, from which we get

$$\frac{\partial \rho}{\partial t} = \nabla \cdot [\rho K \nabla (\Delta f_s)]. \quad (489)$$

The transmission function  $K$  depends on the moisture density  $\rho$ , on the viscosity of the water (which depends on the temperature), and on the nature of the soil. For a given soil at a given temperature, we may therefore write

$$\rho K = \rho F'(\rho) = F(\rho), \quad (490)$$

where  $F(\rho)$  denotes a function of the moisture density  $\rho$ . Equation 489 may therefore be written

$$\frac{\partial \rho}{\partial t} = \nabla \cdot [F(\rho) \nabla (\Delta f_s)]. \quad (491)$$

A solution of this equation obviously gives the moisture density as a function of time and position in the soil mass.

Under steady conditions of flow, including zero flow, we have

$$0 = \nabla \cdot [F(\rho) \nabla (\Delta f_s)]. \quad (492)$$

A solution of equation 492 gives the distribution of moisture as a function of position under the conditions of steady flow, including zero flow. It gives, for example, the moisture density as a function of height above a water table when equilibrium has been established between the upward movement from the water table and the evaporation from the surface of the ground.

The foregoing discussion in this article has been made on the assumption that the kinetic energy of the water is negligible. Where this is not the case, it must be included as another component of the total free

energy. If it is remembered that the total specific free energy represents the maximum amount of useful work possessed by, or obtainable from a substance at constant temperature and external pressure, it is obvious that the kinetic energy term should be included in  $\Delta f_s$ .

In view of the above, let us consider Bernoulli's theorem, which is of great importance in hydrodynamics. To our knowledge, this has never been discussed in terms of free energy. When dealing with incompressible liquids in steady streamline flow, the theorem may be stated as follows:

$$\frac{P}{\rho} + \frac{V^2}{2} + gZ = K = \Delta f. \quad (493)$$

The first term represents the component of the free energy due to pressure, as can be shown from equation 156, since  $P$  here equals  $\Delta P$  and  $\frac{1}{\rho}$  equals  $v$ ; the second, that due to the kinetic energy of the water; the third, that due to its position in the gravitational field (art. 26); and  $K$  is a constant (since we are considering a tube of flow in which the amount of water passing through any cross section in the tube of flow is always the same) equal to the free energy  $\Delta f$ . The equation merely states that at any point along a streamline of flow, the sum of the three component free energies is constant, although the component free energies may vary considerably among themselves.

Suppose we are considering a reservoir from which water is flowing out through an orifice. At the bottom of the reservoir in the orifice, the component free energy due to kinetic energy is a maximum, and that due to position in the earth's gravitational field, a minimum according to equation 493 above; at the top of the reservoir, the component free energy due to kinetic energy is zero, whereas that due to the gravitational field is a maximum; finally, at the bottom of the reservoir far back from the orifice where the water is at rest, we find both the component free energy due to kinetic energy and that due to position in the earth's gravitational field equal to zero, leaving the entire free energy equal to the term

$$\Delta f = K = \frac{P}{\rho}.$$

We thus notice that even for dynamic systems for which Bernoulli's theorem is applicable, where we are dealing with an incompressible liquid under steady flow, the free energy of the liquid is constant throughout a tube of flow, just as was shown to be the case for static systems in equilibrium in article 22.

## DEFINITION OF PRINCIPAL SYMBOLS USED

In the definitions of the following series of terms, some will be found to have several meanings. The context in the articles will indicate which is to be used. A few terms have been omitted from this list since they are used so seldom in the articles and are defined at the place where they are used.

- $a$  maximum work per gram (specific)
- $A$  surface area
- $c$  specific heat; in Raoult's Law, the constant of proportionality
- $c_p$  specific heat at constant pressure
- $c_v$  specific heat at constant volume
- $C$  moisture content in soil
- $d$  differential
- $e$  base of natural logarithms
- $e$  internal energy per gram
- $e_f$  efficiency
- $E$  total internal energy; total energy
- $f$  function
- $f$  absolute value of the free energy per gram (absolute specific free energy)
- $F$  total free energy of a system; force per gram acting on soil moisture
- $\Delta f$  specific free energy with respect to a datum
- $\Delta f_D$  total specific free energy of saturated soil in the dilatometer with respect to the datum
- $\Delta f_{PD}$  component specific free energy of soil moisture in the dilatometer due to its presence in the adsorptive force field surrounding the soil particle
- $\Delta f_{OD}$  component specific free energy of soil moisture in the dilatometer due to the presence of dissolved material which creates an osmotic pressure
- $\Delta f_{PD}$  component specific free energy of soil moisture in the dilatometer due to the hydrostatic pressure in the soil moisture
- $\Delta f_S$  total specific free energy of soil moisture in the normal state with respect to the datum
- $\Delta f_{FS}$  component specific free energy of soil moisture in the normal state due to its presence in the adsorptive force field surrounding the soil particle
- $\Delta f_{OS}$  component specific free energy of soil moisture in the normal state due to the presence of dissolved material which creates an osmotic pressure

- $\Delta f_{PS}$  component specific free energy of soil moisture in the normal state due to the hydrostatic pressure in the soil moisture
- $\Delta f_{oS}$  component specific free energy of soil moisture in the normal state due to the surface-tension effects in the soil moisture
- $\Delta f_{ST}$  total specific free energy of soil moisture at the temperature  $T$
- $g$  acceleration due to gravity; also gravitational force
- $g$  volume of individual compartments of phase space
- $G$  dry weight of soil in grams
- $h$  heat content per gram =  $e + pv$  (in some literature, notably that of mechanical engineering, the term "enthalpy" is sometimes used in place of what we here call "heat content"); a constant in the Maxwell distribution equation =  $\frac{1}{2kT}$ ; height
- $H$  total amount of heat
- $k$  molecular gas constant, that is, Boltzman's gas constant
- $K$  degrees Kelvin or degrees Absolute
- $\bar{K}$  force vector
- $K$  component of a force
- $l$  heat of transition from one phase to another; distance or path of integration in a field of force
- $\ln$  natural logarithm
- $m$  mass of a molecule; total mass; number of mols; mass (in grams) of water in soil
- $m_i$  number of mols of  $i$ th constituent in a solution
- $M$  molecular weight; weight of a mass
- $n_i$  weight in grams of  $i$ th component of a solution
- $N$  total number of molecules; number of molecules per gram (Loschmidt's number)
- $N_i$  number of molecules lying in the  $i$ th cell, interval, or compartment of phase space
- $p$  vapor pressure, or gas pressure
- $p_0$  vapor pressure of datum
- $P$  hydrostatic pressure (may include vapor pressure in general equation)
- $\Delta P_P, \Delta P_o$  hydrostatic pressure, osmotic pressure, respectively, with reference to some datum
- $\Delta P_{os}, \Delta P_{OD}$  osmotic pressure of soil moisture in the normal state and in the dilatometer, respectively
- $\Delta P_{PS}, \Delta P_{PD}$  hydrostatic pressure in soil moisture in the normal state and in the dilatometer, respectively
- $q$  heat energy per gram

$q$	heat of wetting when dry soil is wetted to moisture content $m$
$Q$	heat evolved when the soil, whose dry weight is $G$ grams, is dropped into an excess of water
$r$	radius of curvature
$R$	gas constant per gram
$s$	entropy per gram (specific entropy)
$S$	total entropy of system
$t$	time; total thickness of water film
$\Delta t$	thickness of a liquid surface layer whose total thickness is $t$
$T$	temperature
$\Delta T_o, \Delta T_P$	freezing-point depression due to osmotic pressure and hydrostatic pressure, respectively
$u$	velocity of molecule
$v$	specific volume
$\bar{v}$	partial specific volume
$v_L, v_v$	specific volume of liquid and of vapor, respectively
$V$	total volume; velocity of flow
$w$	work performed by a system or working substance
$w_i$	fraction of the total number of molecules $N$ whose representative points fall in the $i$ th compartment or cell in phase space
$W$	thermodynamic probability of a given macroscopic state
$x_1, x_2, x_3$	positional coördinates in phase space
$x_i$	mol fraction of $i$ th constituent in a solution
$X_i$	weight fraction of the $i$ th component of a solution
$y$	height
$\delta$	mathematical symbol for a variation
$\Delta$	symbol for a small part or element of a quantity; symbol for a finite change
$\epsilon_n$	total energy of a molecule in the $n$ th state, compartment, or cell of phase space
$\theta$	angular measure in degrees; also, in some parts of the discussion, multiple-valued function
$\lambda$	heat of condensation; osmotic potential
$\rho$	density of moisture in the soil, in grams per cubic centimeter of soil; density of air in grams per cubic centimeter; density of water
$\sigma$	surface tension
$\tau$	thickness of the surface layer of water in which properties are different from main body of the liquid
$\Phi$	total potential of soil moisture
$\psi$	pressure potential of soil moisture

$\omega$  gravitational potential

$\nabla \equiv i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y} + k \frac{\partial}{\partial z}$  operator gradient ( $i$ ,  $j$ , and  $k$  being unit vectors in the  $x$ ,  $y$ , and  $z$  directions, respectively)

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# H I L G A R D I A

*A Journal of Agricultural Science Published by  
the California Agricultural Experiment Station*

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VOL. 15

APRIL, 1943

No. 3

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## VASCULAR DIFFERENTIATION IN THE PEAR ROOT<sup>1</sup>

KATHERINE ESAU<sup>2</sup>

### INTRODUCTION

THE PRESENT PAPER deals with the development of the root of *Pyrus communis* L., with special attention to the vascular tissues. Though considerable information is available on root structure of herbaceous plants (Hayward, 1938; Esau, 1940),<sup>3</sup> only one rather complete account of tissue differentiation in a root of a woody species appears to exist in modern botanical literature (Hayward and Long, 1942). The need for such accounts in the teaching of plant anatomy, especially in agricultural institutions, is obvious.

The present problem was selected also because of the writer's interest in the differentiation of the phloem tissue in different organs of seed plants. Since many studies have been made on the phloem of roots of herbaceous plants (review by Esau, 1943), it seemed timely to add some data on the ontogeny of this tissue in a woody root.

### MATERIALS AND METHODS

The root material used in preparing the permanent slides and the photomicrographs was obtained from trees grown in a culture solution by the Plant Nutrition division at Berkeley. The material was killed in a formalin-acetic-alcohol fixing fluid and imbedded in paraffin after ordinary dehydration and clearing in mixtures of ethyl alcohol and xylene.

The roots grown in the culture solution were compared with soil-grown roots from young trees 5 to 6 inches high grown from seeds of the Winter Nelis variety. The latter roots were examined in free-hand sections. No fundamental differences were found between those grown

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<sup>3</sup> See "Literature Cited" for complete data on citations mentioned in the text by author and date of publication.

in culture solution and those grown in soil.<sup>4</sup> All roots examined in the primary state were lateral, since the apices of the seedling taproots were not available. The apical meristem was studied only in the culture-solution material.

### PRIMARY ORGANIZATION OF THE VASCULAR CYLINDER

The apex of the root shows the common separation into the primordial vascular cylinder (or stele), the immature cortex, and the rootcap (plate 1, *B*). In the apical-meristem region, however, only the stele is set off from the other regions with its own initials. The cortex, the epidermis, and the rootcap have a common origin.

The stelar initials form a uniserial layer at the apex of the stele (*si* in plate 10). By periclinal divisions these initials give rise to the innermost part of the stele. Nearer the periphery of the initial layer the divisions are intermediate between the periclinal and the anticlinal, and they are entirely anticlinal in the outermost initial cells. The anticlinal divisions add cells to the pericycle. In plate 10 the pericycle (*p*) is evident as a layer of elongated cells immediately inside the white line on the sides of the stele. In this figure the pericycle can be followed as a uniserial layer directly into the initial region. In other words, the pericycle of this root tip is individualized immediately behind the apical initials. The peripheral derivatives of the stelar initials may, however, undergo a periclinal division before the pericycle is delimited. In any case, the pericycle is histogenetically a part of the stele, and early becomes individualized.

The initial region giving rise to the cortex, the epidermis, and the rootcap, is composed of several layers of cells (*ci* in plate 10, about five layers of cells below the white line in the center of the figure). On the sides of this region anticlinal divisions contribute cells to the cortex. Acropetally the initial cells produce the core of the rootcap by periclinal divisions. The immediate products of these divisions also divide mainly periclinally, so that the youngest part of the rootcap core shows rather orderly-arranged longitudinal files of meristematic cells merging with the initials of the root apex (plate 10). The orderly files of cells remain evident also after the maturation of the rootcap core (plates 1, *B*, and 10). The peripheral portion of the rootcap is produced by periclinal and oblique divisions from the outermost lateral derivatives of the apical meristem. These derivatives are here interpreted as cortical cells and not as epidermis because the latter is set off from the cortex and the rootcap some distance from the apical meristem, after the divisions

<sup>4</sup> Dr. A. S. Foster furnished the killed and imbedded material of roots grown in culture solution, while Dr. L. D. Davis supplied the soil-grown material.

producing the rootcap cease. The peripheral rootcap cells are also aligned in longitudinal files at the source of their origin (plate 10), but this arrangement is somewhat disturbed during the further development of the cells (plate 1, *B*).

Judging by Schüepp's (1926) discussion of root-meristem organization, the pear-root apices described in the present paper belong to the type in which "the entire outer part of the cortex contributes toward the formation of the rootcap" and the stelar initials are independent of those producing the cortex, the epidermis, and the rootcap (Schüepp, 1926, p. 70, type III B). According to Schüepp, certain Rosaceae belong to this group.

The depth of the initial region and the subsequent periclinal divisions in the cortical meristem determine the final thickness of the cortex. Although some doubling up of the longitudinal cell layers occurs throughout the youngest region of the cortex, the addition of new cells through periclinal divisions in its innermost layer is more conspicuous. Plates 10 and 2, *A*, show the result of this meristematic activity. A succession of periclinal divisions in the innermost cortical layer form several rows of narrow cells, densely cytoplasmic. Farther away from the pericycle the cells are larger, their protoplasts less dense. Some anticlinal divisions also occur as the root increases in circumference. After completion of the periclinal divisions the innermost layer of cortical cells undergoes a differentiation as an endodermis (plate 3, *B*, *en*). Eventually the anticlinal divisions and the change in shape of the endodermal cells obscure their close histogenetic relation to the adjacent cortical layer (fig. 1; plate 3, *B*). Since the last periclinal divisions in the inner cortex may not pass all around the stele, the limit between the endodermis and the adjacent cortical layer may appear somewhat disorderly (fig. 1; plate 3, *B*).

The meristematic stele (the procambium) of the root shows a cytologic differentiation immediately behind the apical initials. The central region quickly develops conspicuous vacuoles, and the cells enlarge (plate 10). Comparatively few longitudinal divisions occur here. When the peripheral region is formed by the apical initials these, as was mentioned previously, divide obliquely; and the immediate derivatives undergo periclinal (longitudinal) divisions. Because of these divisions the periphery retains a meristematic appearance somewhat longer than the center of the stele (plate 10). Although nearest the apex the entire periphery of the stele is densely meristematic, some 200 microns higher the peripheral region becomes lobed through the increased vacuolation of certain portions of it. The densely cytoplasmic portion of the procambium becomes broken up into strands, whereas the more highly

vacuolated part assumes, in transverse sections, the appearance of a star (plate 2). Eventually the strands differentiate into the primary phloem, the vacuolated part of the stele into the primary xylem. Thus the xylem and phloem regions become delimited some 200 to 300 microns from the apex, and the metaxylem region is vacuolated before the protoxylem region. The longitudinal divisions that occur in the

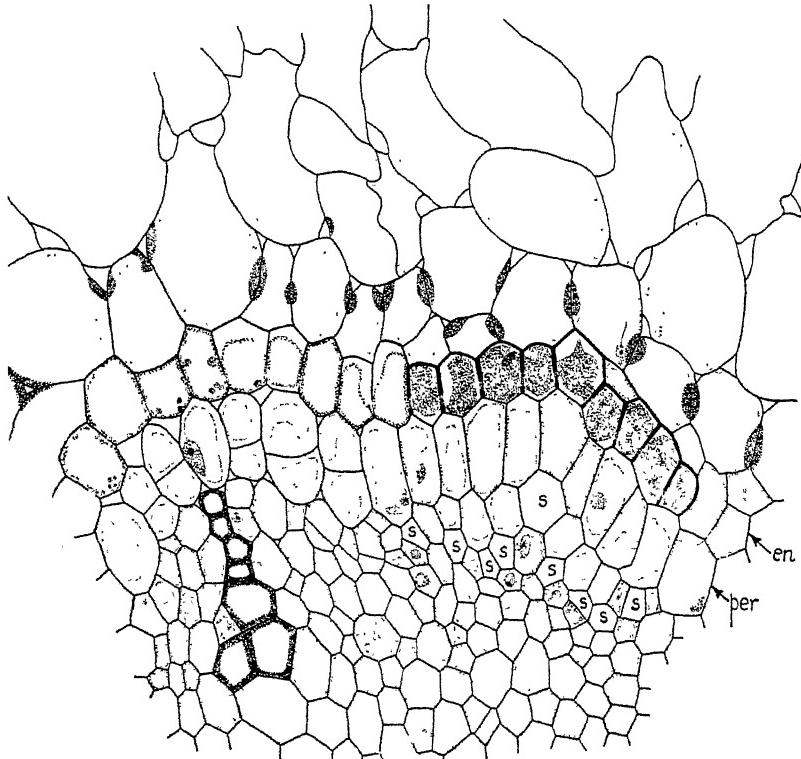


Fig. 1.—Transverse section through portion of root, illustrating the characteristics of the endodermis. The drawing was made from the same section as in plate 3, B (area within the rectangle). Details are: *en*, endodermis; *per*, pericycle; *s*, sieve tube. The faint areas in the endodermal walls indicate sections of the Casparyn strips. Above the endodermis is the cortical layer with localized wall thickenings. ( $\times 621$ .)

peripheral region of the stele last longest on the inner margins of the procambium strands that give rise to the phloem. Later the vascular cambium is initiated in this position (plate 4, B). The young pericyclic cells are as densely cytoplasmic as the future phloem cells, but larger (plate 2, A).

Densely staining inclusions, usually interpreted in the literature as being tannic in nature, appear in the xylem region, the endodermis, and

the cortex (plates 1, *B*, and 2, *A*). The early distribution of the tannic inclusions in the endodermis and in the adjacent cortical layers shows a peculiar relation to the stelar regions. Plate 2, *B*, for example, shows tannin throughout the endodermis and in certain groups of the adjacent cortical cells—groups located next to the regions of the stele that would later have differentiated into the protoxylem. In older stages of root development the tannic inclusions become dispersed throughout the cells instead of remaining confined to the peripheral cytoplasmic layer. This phenomenon is first noticeable in the parts of the endodermis next to the protophloem poles (plate 3, *B*, and fig. 1). Later all endodermal cells and scattered cells within the other root regions stain uniformly densely throughout the protoplasts, apparently because of the dispersed tannic inclusions (plates 3, *A*; 4; 5; 6, *B*; 7).

At levels located about 600 to 700 microns from the apical meristem the first sieve-tube elements differentiate, one in each phloem strand (plate 2, *B*). They mature at unequal levels at the different poles. In the root shown in plate 2, *B*, the section where the first of the five sieve tubes matured was 80 microns nearer the apex than the section where the fifth sieve tube was fully differentiated. The first sieve tubes appear next to the pericycle and are not associated with any cells that could be interpreted as companion cells (plate 6, *A*, sieve tube, *s*, in the center of the figure). Although, as was pointed out before, the pericycle is early individualized, periclinal divisions may occur in the outermost layer of the stele during the organization of the phloem, and a sieve-tube element may differentiate as a sister cell of a pericyclic cell (plate 6, *A*, sieve tube, *s*, in the center of the figure).

These first differentiated phloem elements merit the designation as sieve-tube elements because they have sieve plates on their more or less inclined terminal walls, lack nuclei, and show lightly stained mature protoplasts—all characteristics common to the protophloem sieve-tube elements of angiosperms. (See review by Esau, 1939.) The sieve-tube elements are about 70 microns long immediately upon maturation.

Additional sieve-tube elements differentiate at each pole laterally from the first sieve tubes. In plate 6, *A*, the first sieve tube of one of the phloem strands is in the center of the figure; the second appears to the right. The additional sieve tubes have companion cells but, like the first ones, appear next to the pericycle. When the xylem begins to differentiate, about two sieve tubes occur at each phloem pole. Then still more sieve-tube elements differentiate, some next to the pericycle, others in deeper layers of the procambium strand—that is, centripetally from the first sieve tubes (fig. 1). All these subsequent sieve tubes have companion cells.

Shortly before the xylem begins to differentiate, the entire stele becomes highly vacuolated even in the phloem and the pericycle regions (plate 6, A). The sieve tubes are therefore much less conspicuous in the more mature regions (plate 3, B) than nearer the apex, where they stand out as cells with lightly stained contents among the densely cytoplasmic procambial cells (plate 2, B).

Some 5 mm from the apex the deposition of the secondary walls is initiated in the first xylem elements. These cells differentiate next to the pericycle at the protoxylem poles that alternate with the protophloem poles. The relative position of the early xylem and phloem elements may be judged from figure 1 and plate 3, B, showing two views of the same section taken 2 cm from the apex of the root. The number of the protoxylem poles and, correspondingly, that of the protophloem poles varies, four (plates 3, A, and 5, B), five (plates 2, B; 4; and 5 A), and six (plate 3, B) having been observed in roots of larger, and two in roots of smaller diameters.

The distances from the apex to the first mature xylem and phloem elements were determined by the use of roots grown in culture solution. These distances are not necessarily comparable with those that would occur in roots grown in a different environment, but they vary also in roots grown under similar conditions (Esau, 1941). The differentiation of the sieve tubes in advance of the xylem elements appears, however, to be a usual phenomenon in roots. (See review by Esau, 1943.)

The first xylem elements have very narrow diameters (fig. 1) and in the culture-solution material show scalariform secondary thickenings. One or two elements at each pole are of this nature, the subsequent ones being reticulate and pitted. The later xylem elements have a greater diameter than the first (fig. 1). In soil-grown material the first elements were also scalariform or transitional between spiral and scalariform. Differences in the types of the secondary walls of the protoxylem can be expected in roots grown under different environmental conditions. As has been well established experimentally, the nature of the secondary walls is related to the degree of stretching—caused by the elongation of the entire organ—to which the elements are subjected during their differentiation and thereafter (Smith and Kersten, 1942). Whether the first xylem elements in the pear root are tracheids or vessels has not been ascertained; for convenience they are here called the *xylem elements* or *tracheary elements* (Foster, 1942, p. 80).

In the section shown in plate 3, B, about five to nine sieve tubes occurred at each protophloem pole, and about three to six mature tracheary elements. (In the section shown in figure 1 the two lowermost xylem elements were still immature.) At this stage of development the

endodermis shows Caspary strips. These structures, which are very inconspicuous, appear to be imbedded in the primary wall without forming a thickening on its surface. In sections stained with fast green and safranin they are evident as red wall areas contrasting with the green stain in the rest of the walls. As usual they occur on the radial and transverse walls near the inner tangential walls. The Caspary strips are somewhat more conspicuous in the endodermal cells located at the protophloem poles, probably because in these positions the endodermal walls are somewhat thicker than next to the protoxylem poles (fig. 1).

The cortical layer immediately outside the endodermis is characterized by prominent wall thickenings that resemble those of collenchyma cells (fig. 1; plates 3, *B*; 4; 5; and 7, *A*). These thickenings are not very bright in polarized light, are not lignified, and appear as bands in longitudinal views. Most of them occur on the radial walls, though some are located on parts of walls adjacent to the intercellular spaces (fig. 1; plates 4 and 7, *A*). Occasionally the thickenings also occur in the cortical layer second from the endodermis (fig. 1 and plate 7, *A*). Similar modifications of the inner cortical cells have been mentioned in the literature. Russow (1875, p. 72-73) referred to the similarly thickened cortical layer outside the endodermis as the *exodermis* and commented that the transverse sections of the thick walls resembled the Greek letter Phi. He reported such an exodermis in the roots of the Pomaceae, specifically mentioning *Pyrus*, and in certain other families of dicotyledons and gymnosperms. Guttenberg (1940, p. 121-22) calls this layer the *inner cortical sheath* and records its presence in the Rosaceae.

At the stage of root development illustrated in plate 3, *B*, and figure 1, the pericyclic cells show pronounced radial elongation and divide periclinally next to the protoxylem poles. As viewed in longitudinal sections the pericyclic cells appear short, in sharp contrast to the long cells of the adjacent vascular tissues. Plate 8, *A*, illustrates this difference in a root somewhat older than the one shown in plate 3, *B*.

On the basis of our present information regarding the stages in the differentiation of the primary vascular tissues (review by Esau, 1943), the terms *protophloem* and *protoxylem elements* are here applied to the phloem and xylem cells which mature in advance of the other vascular elements in the root and which by their position mark the pattern of differentiation followed by the primary vascular tissues. As is usual in roots, the phloem following the protophloem in time of appearance (that is, the metaphloem) and the subsequent primary xylem (the metaxylem) differentiate centripetally from the protophloem and protoxylem poles respectively. The phloem also spreads laterally from its

points of initiation, so that the protoxylem strands eventually appear as narrow strips of tissue crowded between the broad phloem strands (plate 4, A).

The demarcation between the protophloem and the metaphloem, and between the protoxylem and metaxylem is usually drawn somewhat arbitrarily (Esau, 1943). The first sieve-tube element at each pole in the pear root is the largest in diameter among the primary sieve tubes and lacks companion cells (plate 3, B, and fig. 1). These are probably rather common characteristics of the first sieve tubes of dicotyledonous roots (Esau, 1935, 1940, 1941). In time of appearance the first sieve tubes in the pear root are less sharply set off from the following sieve tubes than they are in tobacco-root tips studied by the present writer (Esau, 1941). In the pear root, as was mentioned earlier, one or two additional sieve-tube elements having rather narrow diameters and associated with companion cells differentiate at each pole before the first xylem elements begin to show a deposition of secondary walls.

Since there is no sure basis for delimiting the different parts of the primary vascular tissues (review by Esau, 1943), the first three or four elements at each pole (elements early crushed because of subsequent growth changes in the root) are here classified as protophloem and protoxylem elements. Conceivably, the distinctness with which the first vascular elements are set off from the subsequent ones in time of appearance is determined largely by the degree of elongation of the roots. Judging by the nature of the secondary walls of the protoxylem in the pear root (scalariform, rather than annular or spiral) and by the small amount of distortion that these walls show in sections of root with secondary growth, the roots used in this study must have been elongating only slightly, if at all, after the protoxylem matured. The lateral pressure of the adjacent living cells seems in this material to have been the principal cause of distortion of the protoxylem elements. Plate 5, B, indicates the encroachment of the adjacent cells upon the protoxylem, particularly at the protoxylem pole in the lower part of the figure. The crushing and the obliteration of the protophloem sieve tubes and their companion cells, if these are present, are rather conspicuous (plate 4, B, and 7).

By the definitions given above the sieve-tube elements in plate 6, A, are protophloem cells. The mature intact sieve-tube elements in plate 7, A, are metaphloem cells. The two immature sieve tubes at the lower left in plate 7, A, are the first secondary sieve tubes in this bundle. Certain cells of parenchymatous appearance in plate 7, A, are phloem-parenchyma cells, whereas others are much elongated elements and eventually differentiate as fibers. Plate 7, B, illustrates the early stage

in secondary-wall formation in the fibers of the protophloem, whereas plate 8, *B*, shows one of these fibers on the outer limit of the phloem in longitudinal view. Later, fibers differentiate in the metaphloem also. The primary-phloem fibers together with the fibers of the earliest secondary phloem form, in old roots, compact strands on the outer periphery of the vascular cylinder (plate 1, *A, fb*). The sieve tubes and companion cells are all obliterated in this region, while the parenchyma cells are much dilated, especially in the tangential direction. The parenchyma cells contain inclusions such as starch, tannin, and crystals; some of them become sclerified as stone cells. As the present writer has frequently emphasized (Esau, 1938, 1939, 1943), fibers that appear on the outer periphery of the vascular cylinder in stems commonly arise in the phloem. Lloyd (1911, p. 94) has given good evidence that the peripheral fibers of the root stele in *Parthenium* are phloem fibers.

The metaxylem comes to occupy the entire center of the stele (plates 1, *A*; 5, *B*; and 8, *A*). Vessels, tracheids, and xylem parenchyma, all prominently pitted, occur in this region. Though the metaxylem is defined before the protoxylem in the meristematic stele, it matures rather slowly, so that its secondary-wall formation is not terminated before cambial activity sets in (plate 4, *B*).

### SECONDARY GROWTH IN THE ROOT

As has been pointed out, the procambial divisions last longest on the inner margins of the phloem bundles. During the differentiation of the protophloem and protoxylem, the procambial cells in this position enlarge somewhat and vacuolate so that they merge imperceptibly with the immature phloem and xylem cells (plates 6, *A*, and 4, *A*; fig. 1). After the final delimitation (but not maturation) of the primary regions in the stele (plate 4, *A*) the divisions on the inner margins of the phloem bundles are resumed and now result in radial series of narrow cells (plate 4, *B*). These are divisions initiating the secondary growth of the vascular tissues.

As shown in plate 4, *B*, the first cambium occurs in isolated curved strips on the inner sides of the phloem bundles. This meristem, after producing some secondary xylem elements, becomes united into a continuous layer between the xylem and the phloem by the meristematic activity of the pericyclic cells located outside the protoxylem poles. Plates 4, *B*, and 5 show how markedly this early production of secondary xylem changes the outline of the cambium region in transverse sections. First it appears in the form of curved arcs, bulging toward the center of the root (plate 4, *B*); then the arcs are straightened out (plate 5, *A*). After this position is attained, periclinal divisions in the pericycle out-

side the protoxylem also form some cambium, and thereby this meristem becomes a continuous, more or less cylindrical layer of tissue around the entire circumference of the xylem. In plate 5, *B*, this stage had almost been reached. As previously indicated, the pericyclic cells divide periclinally at a very early stage in the primary development of the root (fig. 1). These divisions probably prepare the formation of the vascular cambium in this position.

In common with the vascular meristem of arborescent dicotyledons, the cambium of the pear root is composed of fusiform and ray initials. The pericyclic cells outside the protoxylem give rise to ray initials, so that vascular rays radiate from the protoxylem poles through the secondary vascular tissues (plate 1, *A*). In agreement with Barghoorn's (1940) observations on ray formation in roots, the rays formed at protoxylem poles in the pear root are the first multiseriate rays in the secondary xylem. The cambium arising in the procambium inside the primary-phloem strands also produces rays, but the earliest formed in this position are uniserial.

Plate 1, *A*, shows a pear-root section with considerable secondary growth of the first season. The primary xylem, a five-pointed star, is imbedded in the secondary xylem. In the latter the wide pores (representing transverse views of vessels) and the rays are the conspicuous structural features detectable at this magnification. Plate 9, *B*, shows a section of the secondary xylem from plate 1, *A* (area delimited by a rectangle), in greater detail. Four rays are visible in this section, the one to the left being a multiseriate ray that arose in the pericycle outside the protoxylem. (Compare with plate 1, *A*.) The rays are parenchymatous and contain starch grains and tannin. In the longitudinal system the cells having the widest diameters (plate 9, *B*) are vessels. Some of the narrower cells are also tracheary elements; others are fibers and xylem-parenchyma cells. Starch grains and tannin occur in the latter.

The major part of the tissue located outside the cambium in plate 1, *A*, is phloem (*ph*). The rest is pericycle and periderm. The multiseriate and uniserial parenchymatous phloem rays that are continuous with the xylem rays divide the secondary phloem into blocks of tissue composed of sieve tubes, companion cells, phloem parenchyma, and some fibers. A portion of the secondary phloem from plate 1, *A* (area delimited by a rectangle) is depicted at high magnification in plate 9, *A*. A multiseriate ray occurs to the left. In the lowermost part of this figure appears the cambium. Then follows the functioning part of the phloem with mature sieve tubes (*s*). Farther away from the cambium the sieve tubes and the companion cells are partly crushed among the enlarged parenchyma cells. This is the phloem part which, according to a common

concept, is no longer concerned with longitudinal conduction. The enlargement of the phloem parenchyma cells becomes particularly conspicuous towards the periphery of the stem, where a considerable tangential dilation occurs in all living cells of the phloem and pericycle.

The outer limits of the phloem may be determined by the position of the fibers which, as was described earlier, arise in the phloem, the earliest ones being in the protophloem (plate 7, *B*). The pericycle gives rise to the cork cambium. The formation of this meristem is preceded by an increase in thickness of the pericycle. As previously mentioned, the earliest tangential divisions in this region occur outside the protoxylem (fig. 1, plate 3, *B*). Later, such divisions spread all around the periphery of the stele (plates 5, *A*, and 7, *B*) and are repeated several times, so that the pericycle shows a marked increase in thickness (plates 5, *B*, and 8, *B*). In plate 5, *B*, the excessive width of the pericycle to the right of the stele results from growth phenomena associated with the development of branch roots. The latter are surrounded at their bases by collars of tissue resulting from a proliferation of pericyclic cells. In sectional views these collars resemble lenticels, provided the branch roots associated with them do not appear in the same view (plate 1, *A*, below). True lenticels have not been observed in the present material.

During the increase in the circumference of the stele through the cambial activity and the proliferation of the pericycle, the cortex together with the endodermis is crushed and sloughed off. Plate 3, *A*, shows the first splitting of the cortex. No cortex occurs in the section in plate 1, *A*.

The new pericycle cells are aligned in rather orderly radial rows (plates 5, *B*, and 8, *B*). The outer cells become tangentially stretched and radially compressed as the stele increases in circumference. After undergoing suberization they serve as a protective layer before the cork cambium and cork are formed in one of the deeper layers in the pericycle. In the material used in this study most of the sections showed only the first-formed periderm. Occasional roots showed isolated strips of cork cambium within the secondary phloem.

#### SUMMARY

The apical meristem of the root shows two sets of initials. One set, one layer deep, produces the stele with the pericycle; the other set, several layers deep, gives rise to the cortex, the epidermis, and the central core of the rootcap. The peripheral portion of the rootcap arises from the youngest cortical cells.

Within the stele the pericycle is individualized almost directly behind the apical initials. The phloem and the xylem regions are clearly

delimited before any vascular elements differentiate, the phloem region being composed of small, densely cytoplasmic cells, the xylem region of larger and more highly vacuolated cells.

The first protophloem sieve tubes mature in advance of the first protoxylem elements. The protophloem and the protoxylem appear next to the pericycle and alternate with each other. The number of the protophloem and protoxylem poles varies in roots of different diameters.

The differentiation of the metaphloem and metaxylem proceeds in the usual centripetal manner from the protophloem and protoxylem poles respectively.

The endodermis is a uniseriate layer with Casparyan strips. The cortical layer next to the endodermis has localized thickenings on its walls.

The cambium arises in the manner characteristic of roots. It first appears on the inner side of the phloem bundles, then becomes continuous across the pericycle cells located outside the protoxylem. The secondary vascular tissues show the common characteristics of these tissues in woody dicotyledonous roots.

The pericycle, which is at first uniseriate, becomes multiseriate by tangential divisions. The outermost cells resulting from these divisions become cork cells, and beneath them arises a cork cambium. The cortex with its endodermis is sloughed off in connection with the secondary activity in the stele.

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## PLATES



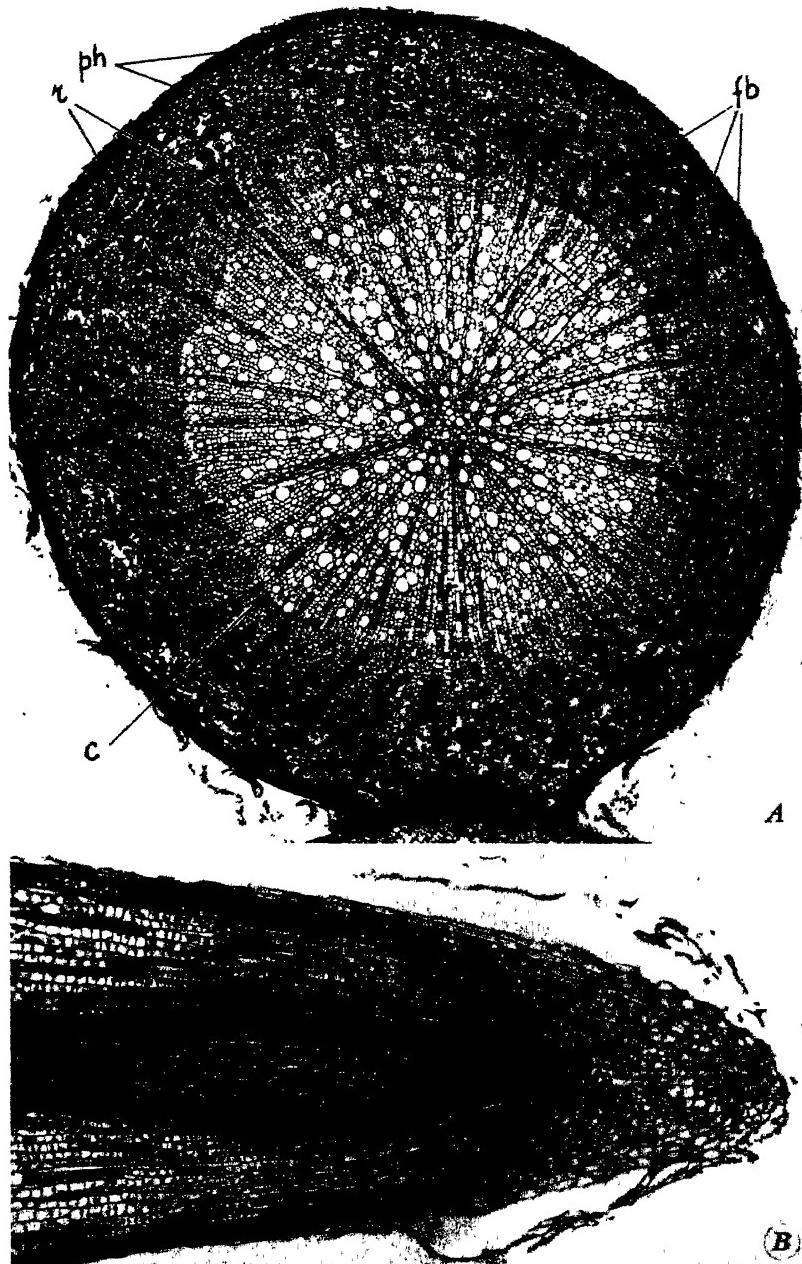


Plate 1.—*A*, Transverse section of a root with considerable secondary growth. Details are: *c*, cambium; *fb*, fibers; *ph*, phloem; *r*, rays. The rectangles delimit the areas of secondary phloem and secondary xylem depicted at high magnification in plate 9. The small arrowheads in the center indicate the five protoxylem poles. *B*, Longitudinal section of a root tip showing the apical meristem and the regions immediately derived from it. (*A*,  $\times 50$ ; *B*,  $\times 90$ .)

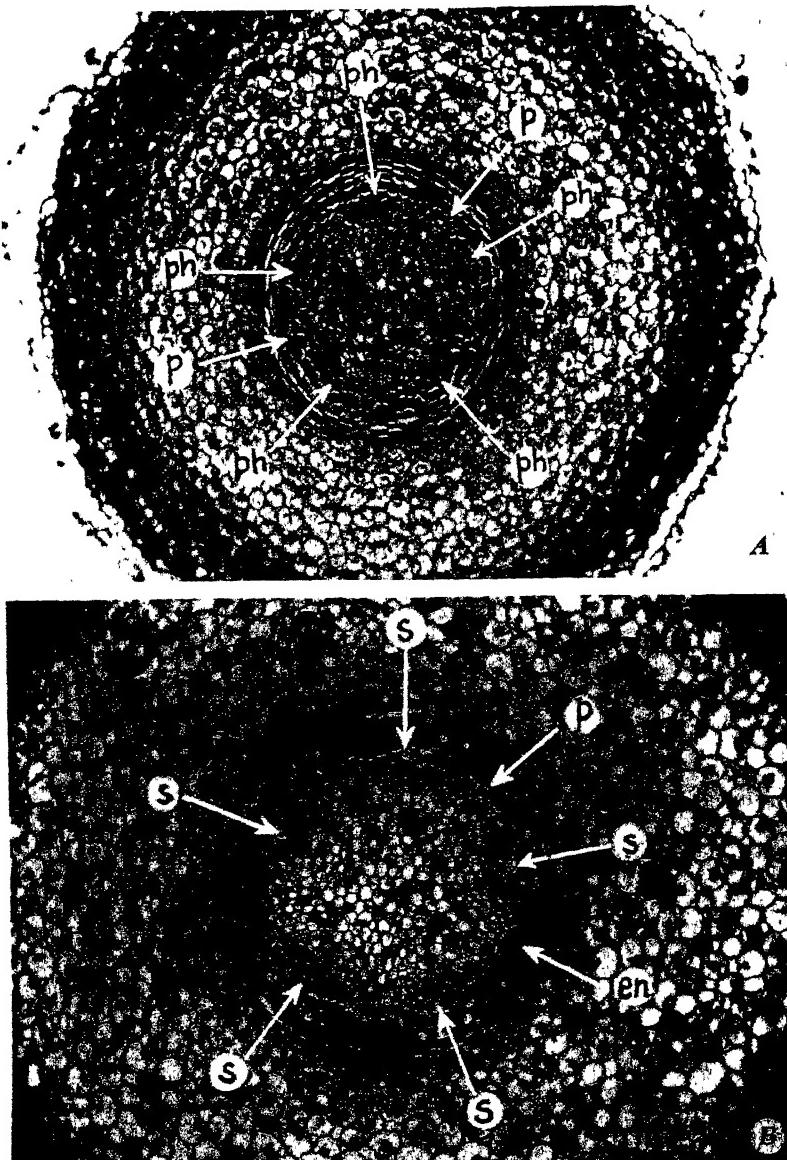


Plate 2.—Transverse sections of a root tip taken 280 microns (A) and 750 microns (B) from the apical meristem. Details are: *en*, endodermis; *p*, pericycle; *ph*, protophloem pole; *s*, sieve tube. (Both  $\times 180$ .)

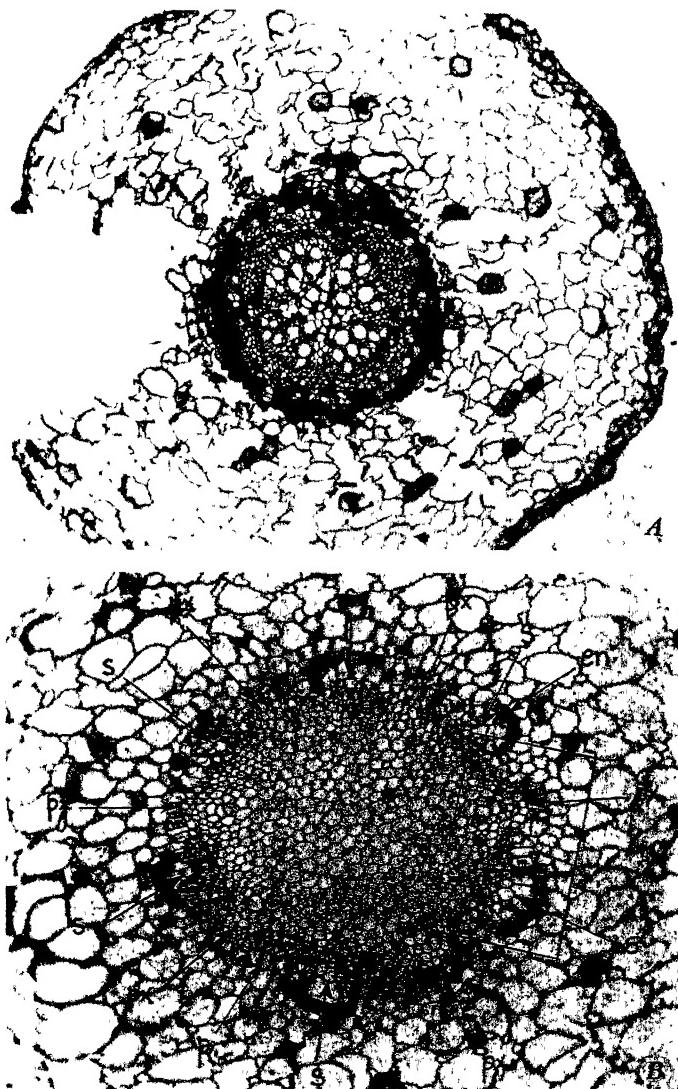


Plate 3—*A*, Transverse section of root, showing splitting of cortex. The stage of development of the vascular tissues is comparable to that in plate 5, *B*. *B*, Transverse section of root taken about 2 cm from the apex. It illustrates an early stage of phloem and xylem differentiation. Details are: *en*, endodermis; *p*, pericycle; *px*, protoxylem; *s*, sieve tube. The rectangle delimits the area depicted at higher magnification in figure 1. (*A*,  $\times 90$ ; *B*,  $\times 180$ .)

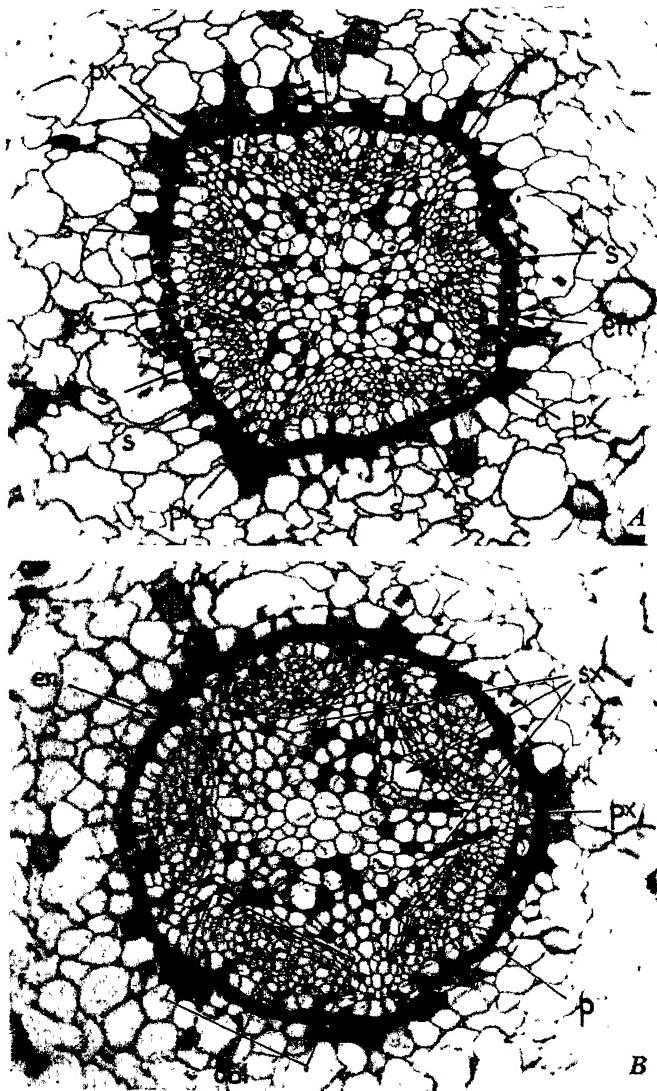


Plate 4.—Transverse sections taken about 4 cm (A) and 5 cm (B) from the apex of the root. A illustrates the stage just before the beginning of cambial activity. In B the first secondary xylem elements are present. Details are: en, endodermis; obl, obliteration of sieve tube; p, pericycle, px, protoxylem; s, sieve tube; sx, secondary xylem. The rectangle in B delimits the area shown at higher magnification in plate 7, A. (Both  $\times 180$ )

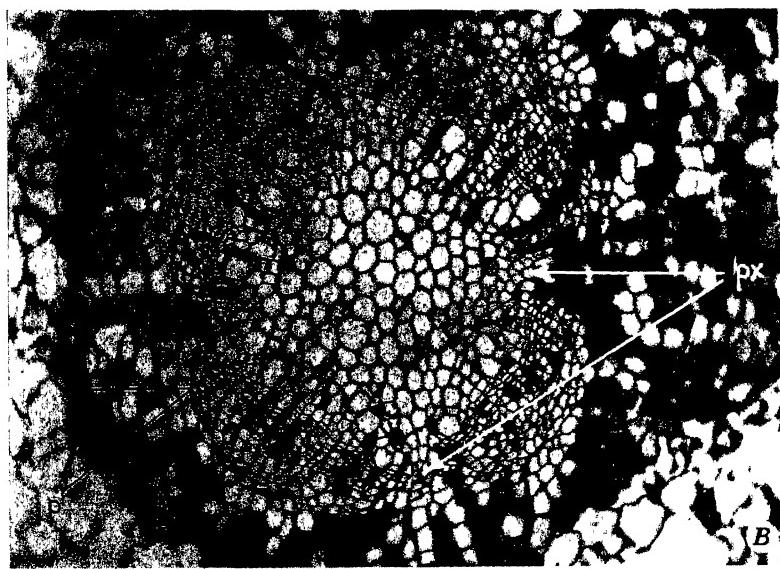
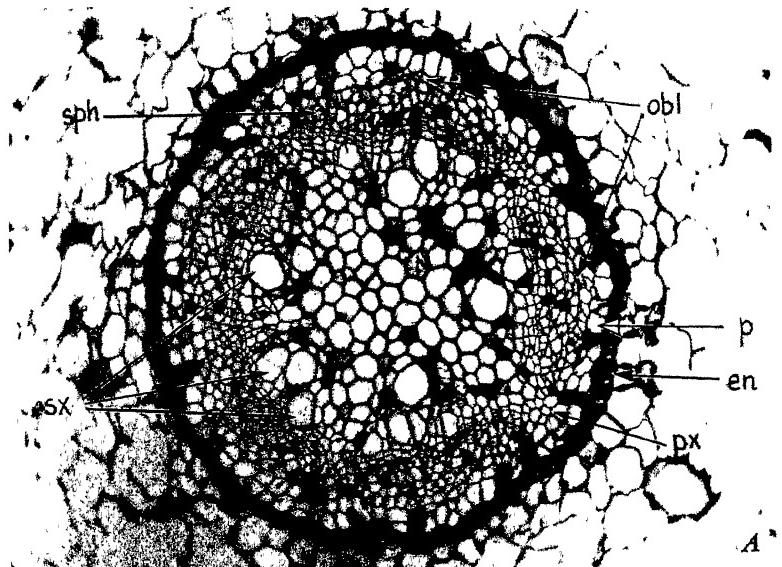


Plate 5.—Transverse sections taken about 7 cm (A) and 9 cm (B) from the apex of the root. A illustrates the stage just before the splitting of the cortex. In B the cortex was split. Five protoxylem poles occur in A, four in B. Details are: en, endodermis; obl, obliteration of sieve tube; p, pericycle; px, protoxylem; sph, secondary phloem; sx, secondary xylem. (Both  $\times 180$ .)

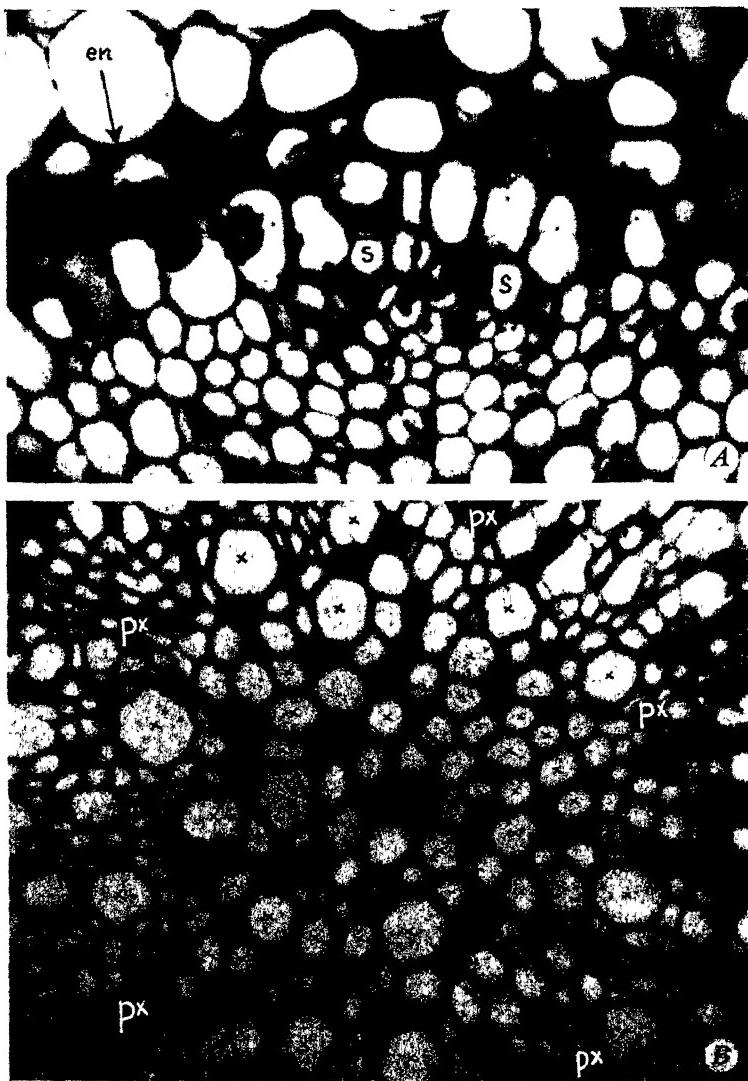


Plate 6.—A, Transverse section through a protophloem pole with two sieve tubes (*s*) taken 1,720 microns from the apical meristem *B*, High-power view of the primary-xylem region from a section somewhat older than that shown in plate 5. *B*. Details are as follows: *en*, endodermis; *p*, pericycle; *px*, protoxylem; *s*, sieve tube. In *B* the tracheary elements have been indicated by small crosses (*A*,  $\times 810$ ; *B*,  $\times 360$ .)

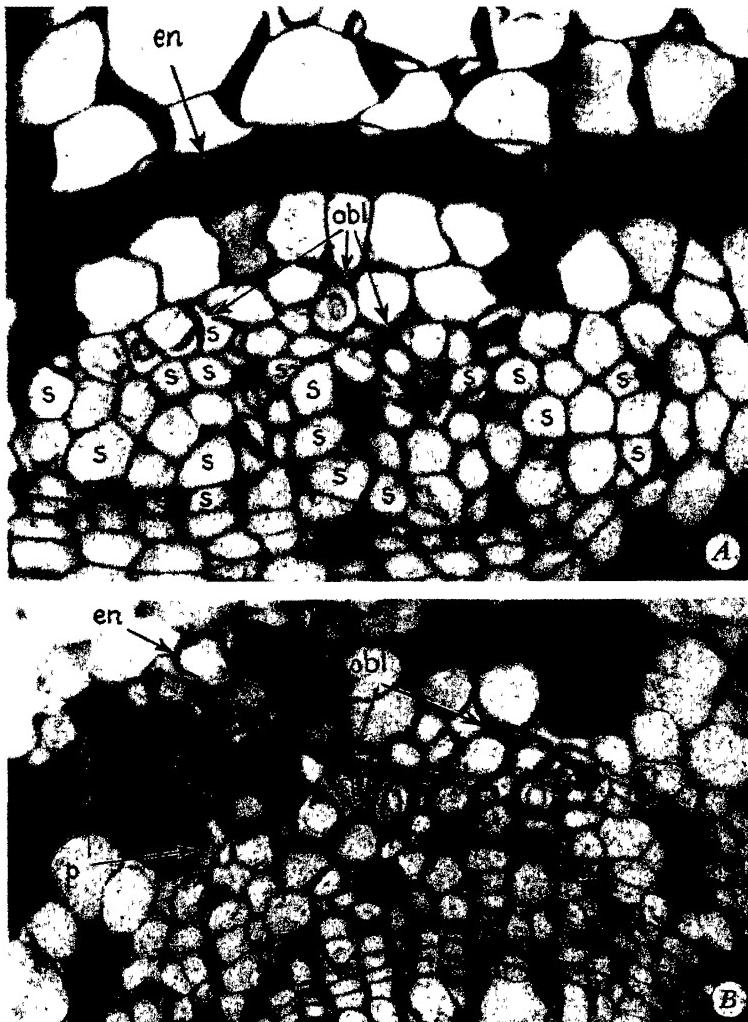


Plate 7.—*A*, High-power view of portion of transverse section figured in plate 4, *B* (area within the rectangle). It shows the primary phloem, the endodermis, and the inner cortical sheath above the endodermis. *B*, High-power view of portion of transverse section figured in plate 3, *A*. It shows the primary phloem during the early stage of fiber development and the first secondary phloem near the cambium. Details are: *en*, endodermis; *fb*, fiber; *obl*, obliteration of sieve tubes; *p*, pericycle; *s*, sieve tube. The sieve tubes in *B* are marked by dots (*A*,  $\times 810$ , *B*,  $\times 540$ )



Plate 8.—*A*, Radial longitudinal section of root at the end of primary growth as in transverse view in plate 5, *A*. The cells marked with small crosses are pitted tracheary elements. *B*, Radial longitudinal section of a root sampled after the proliferation of the pericycle as in transverse section in plate 5, *B*. Details are: *en*, endodermis; *fb*, fiber in the phloem; *p*, pericycle; *ph*, phloem, *r*, ray (Both  $\times 180$ .)

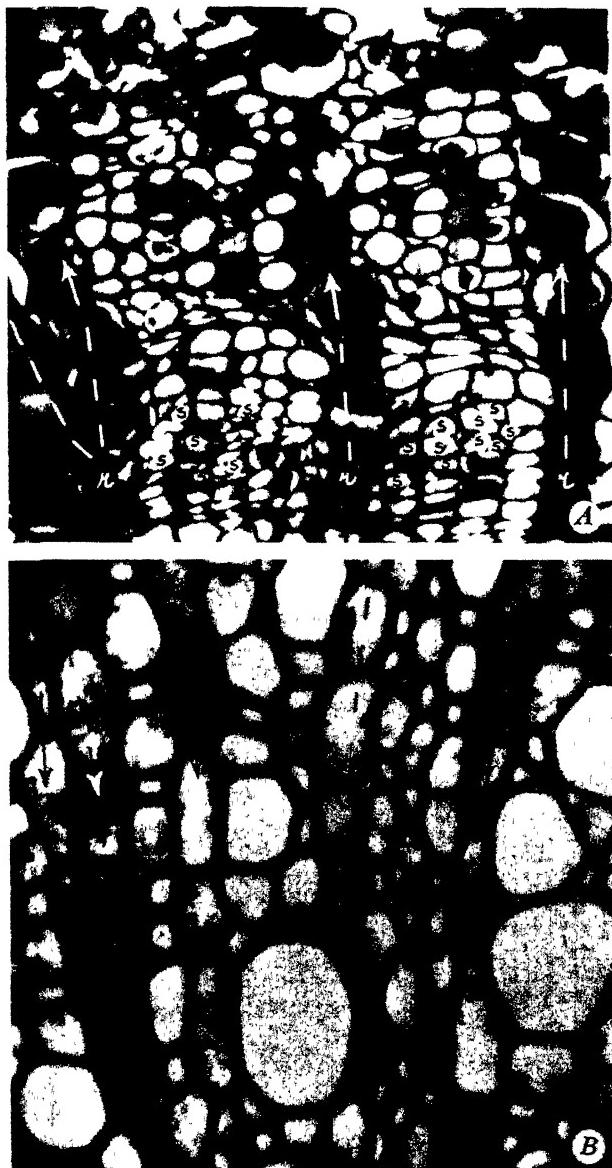


Plate 9.—Portions of transverse sections of secondary phloem (A) and secondary xylem (B) from the same section as in plate 1, A. (areas delimited by rectangles) The letter *s* in A indicates the sieve tubes in the mature phloem. Above this region is the old phloem with partly crushed sieve tubes and prominent parenchyma cells. The letter *r* indicates the rays in both figures. (Both  $\times 360$ .)

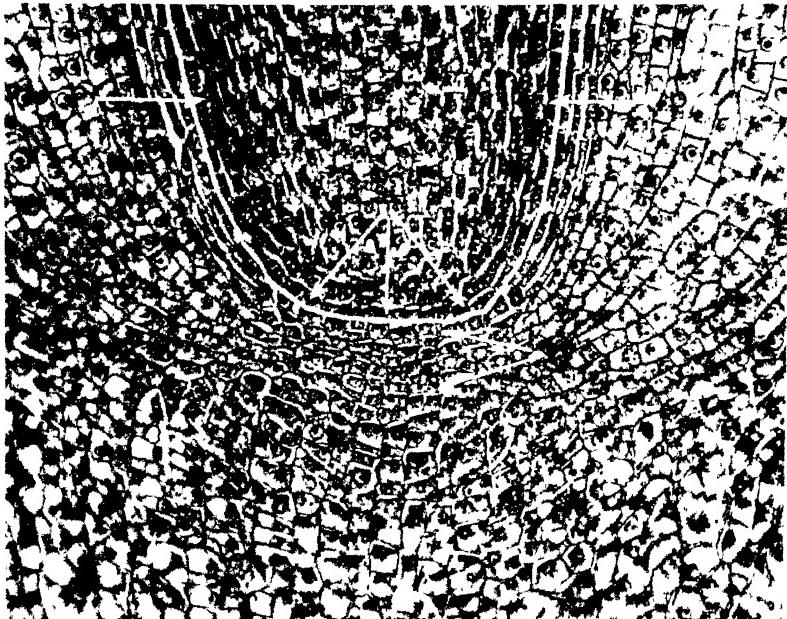


Plate 10.—Median longitudinal section of root tip through the apical meristem region. The limits of the stele are indicated by a white line. Details are: *ci*, cortical initials; *p*, pericycle, *si*, stellar initials. ( $\times 300$ )

ONTOGENY OF THE VASCULAR BUNDLE  
IN *ZEA MAYS*

KATHERINE ESAU



# ONTOGENY OF THE VASCULAR BUNDLE IN ZEA MAYS<sup>1</sup>

KATHERINE ESAU<sup>2</sup>

CONTINUING THE STUDIES on the anatomy of crop plants, with special emphasis on vascular differentiation (Esau, 1936a, 1938, 1940, 1941),<sup>3</sup> the writer has selected *Zea Mays* L. as a representative of the monocotyledons. Though the vascular system of this plant has often been studied (Strasburger, 1891, p. 329-63; Hayward, 1938, chapter 5; Sharman, 1942), the ontogeny of the vascular strand merits further detailed investigation in view of the many unsolved problems of vascular differentiation in the monocotyledons. (See review by Esau, 1943.) The present paper concerns, first, the developmental relation between the vascular tissues and the bundle sheath—a structure characteristic of the vascular bundles in the Gramineae. Second, it attempts to elucidate the nature of the meristem producing the vascular bundles. Literature gives conflicting answers to the question whether this meristem—some or all of it—should be interpreted as *procambium* or *cambium*. (See review by Esau, 1943.)

The vigorous vegetative side shoots used as material for slides were obtained from the plants of the Golden Cross Bantam variety, growing in an open field. In preparing the permanent slides a common paraffin method (Esau, 1941) was followed. Free-hand sections were employed for examining the gross structural features.

## THE MORPHOLOGY OF THE VASCULAR BUNDLE

For clarity the structure of the vascular system and of the mature vascular bundle will be considered before the ontogenetic details. Since the recent works on this subject (Hayward, 1938; Sharman, 1942) have not cited Strasburger's (1891, p. 329-63) thorough treatment of the morphology of the vascular tissues in *Zea Mays*, his description is here reviewed in the light of the present observations and the findings of other investigators.

*The Vascular System.*—In common with the other monocotyledons, *Zea* has numerous "parallel" vascular bundles in the leaf blade and the leaf sheath. (Since the bundles converge and fuse at the tip of the leaf, they are not truly parallel.) Large bundles alternate with small. Within the stem the prolongations of the leaf strands, the *leaf traces*, appear as

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<sup>3</sup> See "Literature Cited" for complete data on citations, mentioned in the text by author and date of publication.

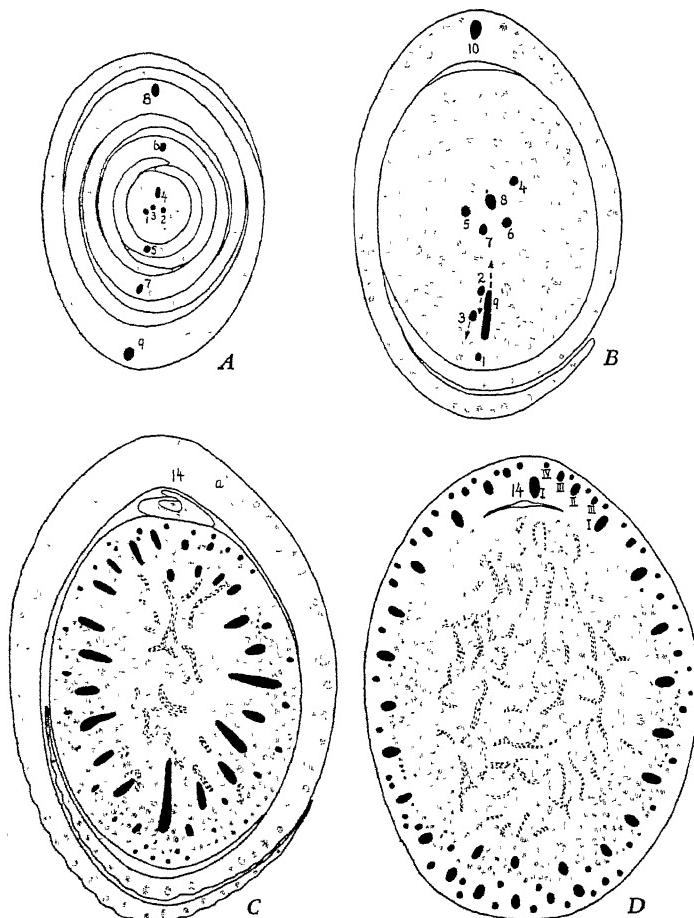


Figure 1.—Diagrams of transverse sections through a shoot taken the following number of microns below the apex: *A*, 450; *B*, 1,030; *C*, 2,690; *D*, 3,320. One or more leaves ensheathe the stem in *A* to *C*. In *A* and *B* the median leaf bundles or traces are shown in black. Traces 1 to 3 appear in their median positions within the stem in *A*, but are near the periphery in *B*. The arrows in connection with the traces 2 and 3 in *B* indicate that these two traces occurred still nearer the periphery at lower levels of the stem. In *C* the traces of leaf 13 are shown in black. The large traces, which at lower levels occur near the center of the stem, have at level *C* a somewhat oblique transverse course. In *D* the traces of leaf 14 are shown in black. The traces of leaf 13 in *C* were cut below the insertion of leaf 13, whereas the traces of leaf 14 in *D* appear at the level where leaf 14 is united with the stem. The small curved bundles indicated by broken lines in *C* and *D* are the horizontal traces leading to the axillary buds and adventitious roots. At *a* in *C* appears a transverse connection between two longitudinal strands in leaf 14. The Roman numerals in *D* indicate the order of appearance of the bundles accompanied by these numbers. (*A* and *B*,  $\times 20$ ; *C* and *D*,  $\times 10$ .)

scattered vascular bundles (fig. 1, *B*). The different traces of one leaf occur at different depths within the stem. If the traces of a given leaf are studied in successive sections, downward from the node at which this leaf is attached to the stem, their course is as follows: Within the node the large bundles bend inward, whereas the small ones remain near the periphery of the stem (fig. 1, *C*). The median bundle bends so strongly that it approaches the center of the stem. In figure 1, *A*, the median traces 1, 2, and 3 appear in their innermost positions; trace 4 is approaching such a position. In figure 1, *B*, the median traces 4 to 8 occur around the center of the axis. The other large bundles come to occupy intermediate positions between the peripheral and the central. With slight alterations in their positions the traces extend downward within the stem through several internodes; then the larger traces become clearly reoriented to a peripheral position. Figure 1, *B*, shows the median trace of leaf 1 in a peripheral position, whereas traces 2 and 3 are approaching this position. Usually the median trace appears in its peripheral position on the side of the stem opposite the median part of the leaf to which this trace belongs. In this respect traces 1 and 3 in figure 1, *B*, deviate from the ordinary condition. The reorientation of the large traces is accompanied by a basipetal diminution in size, so that in their peripheral prolongations these traces are as small as the leaf traces whose longitudinal course is entirely peripheral.

The vascular system of *Zea* closely corresponds with that of the so-called "palm-type," whose features Haberlandt (1914, p. 383) sums up. Sharman (1942, p. 259) opposes this comparison because the large bundles lateral to the median "do not approach the center of the stem, but maintain a vertical course." Figure 1, *C*, shows that the large lateral traces, as well as the median, have a horizontal course at the node and approach the center of the axis, though finally the laterals occupy a less central position than the median strand.

The traces of a given leaf remain discrete through variable lengths of the stem. Strasburger (1891, p. 351-52) found the larger traces to be free of connections through longer distances than the smaller bundles. He followed the median traces through about six internodes. Sharman (1942) and the present writer distinguished median strands within eight or more internodes in the youngest shoot parts. Traces 1 and 2, for example, are still discrete in the ninth internode in figure 1, *B*. The smallest peripheral bundles may fuse with others at the first node or may continue free to the next lower node (Strasburger, 1891).

Certain horizontal bundles occur in the nodal plates and in the peripheral portion of the internodal base (fig. 1, *D*). In plate 10 these bundles are cut mostly transversely and appear as small groups of

dense cells among the large longitudinal traces. According to Strasburger (1891, p. 346-47), the horizontal bundles of the internode rise from the node below and connect with the axillary buds and the adventitious roots. Sharman (1942) places all the horizontal bundles in the base of the internode, interpreting them as prolongations of the youngest peripheral traces formed after these traces reach the base of the internode in their basipetal course of development. Judging by the position of the leaf bases and the horizontal bundles, the section in plate 10 does not substantiate Sharman's statement that horizontal bundles are not formed within the node. In addition, figure 1, C, shows some transverse bundles at the same level where the traces of leaf 13 have a horizontal course within the node of this leaf.

*The Vascular Bundles of the Leaf Sheath, the Internode, and the Node.*—The vascular strands vary in structure in the different parts of their course. There are also differences between bundles of different size. Plate 9, B, depicts a large bundle from a leaf sheath. In structure it resembles the central bundles of the internode. (Compare with plate 25 in Artschwager, 1925.) It is the best-known type of *Zea* bundle. The xylem and the phloem are arranged collaterally and, when mature, enclose no meristem between them. The tracheary elements of the protoxylem (annular and spiral vessels), which mature before the stem or the leaf elongates, are disintegrated in the mature bundles; in their place appears a large intercellular space, the *protoxylem lacuna* (plate 9, B, l). The lacuna is surrounded by xylem parenchyma. Frequently an annular or spiral vessel appears in the median position of the bundle next to the lacuna (plate 9, B). Since this vessel matures after the elongation of the stem or sheath and is not destroyed by this growth, it may be regarded as the first metaxylem element. On both sides of the bundle (plate 9, B) occur two other large metaxylem vessels, usually with pitted or reticulate-pitted secondary walls. The small-celled tissue between the two lateral metaxylem vessels (in contact with them) is a mixture of xylem parenchyma and narrow tracheary elements. The latter are small vessels (Strasburger, 1891, p. 330; Cheadle, 1942), varying in number; some of them usually touch the large vessels (plate 9, B). Like the conducting elements, the parenchyma of the metaxylem has lignified walls and prominent elongated pits.

The phloem is composed of rather large sieve tubes and small companion cells in a more or less orderly pattern. The phloem shown in plate 9, A and B, is metaphloem. The protophloem is crushed in mature bundles (*obl* in plate 9). The last procambial cells between the xylem and the phloem differentiate as parenchyma, which separates the two conducting tissues from each other. This separation is not necessarily

complete. Phloem cells (companion cells and sieve tubes) frequently are in contact with the lignified xylem parenchyma. (In plate 9, *B*, the sieve tube at *st* and its companion cell lie next to a xylem-parenchyma cell.)

The large bundles are enclosed in a bundle sheath having lignified walls. The sheath cells are compactly arranged, with no intercellular spaces among them or between them and the vascular cells. At the xylem and the phloem poles of the bundle the sheath is two to several layers thick, the cells being sclerenchymatous, long, and tapering. On the flanks of the bundles the sheath cells are shaped like parenchyma cells; they have rounded pits, in contrast to the slitlike pits of the prosenchymatous sheath cells. Often the sheath is uniserial on the flanks of the bundle (plate 9, *B*); but it may be thicker. As far as could be ascertained, the sheath cells have protoplasts in mature state, in agreement with Strasburger's (1891) description.

The sheath cells are in contact with the xylem parenchyma and frequently also with the two lateral metaxylem vessels (plate 9, *B*). According to Strasburger (1891), no pits occur between the vessels and the sheath cells, although these structures are very prominent between the vessels and the xylem parenchyma cells. The sheath cells touch the crushed protophloem, but are separated from the metaphloem by a layer of parenchyma (plate 9, *B*). According to Strasburger (1891), these parenchyma cells may show lignification in the walls adjacent to the sheath.

The small peripheral bundles of the stem and the small strands of the leaf sheath have less vascular tissues and smaller bundle sheaths than the large bundles. Since the smallest bundles mature after the organs containing them have ceased to elongate, they show little effect of stretching. No protoxylem lacuna is present, or the protoxylem and the protophloem are entirely lacking.

The central or near-central bundles that traverse the nodes vertically also show little effect of elongation in the nodal region, in that their protoxylem is not converted into a lacuna. Fusions of bundles are common in this region. Traces having a horizontal course in the node (fig. 1, *C*, the large traces of leaf 13) show an arrangement of tissues different from that in the longitudinal bundles: the xylem tends to surround the phloem (amphivasal bundles). The nodal anatomy is further complicated by anastomoses, fusions, and the connections with the horizontal system already mentioned (fig. 1, *D*).

*The Bundles of the Intercalary-Meristem Zone.*—*Zea*, in common with the other Gramineae, has the so-called "intercalary-meristem" regions at the base of each leaf sheath and each internode of the stem.

It is commonly stated in the literature that these meristems cause the internodes and the leaf sheaths to elongate for some time after being laid down by the apical meristem (Troll, 1935, p. 109). As Haberlandt (1914, p. 182) implies, fundamentally the intercalary elongation of the shoots in the Gramineae is comparable with that of the dicotyledonous stems. Haberlandt also points out that "there are comparatively few Phanerogams in which cell-formation and -extension are strictly confined to the apical region of the axis and the youngest internodes." In the Gramineae and the Cyperaceae, however, the intercalary growth is very striking, since it appears to be rather clearly separated from the apical growth and occurs within a comparatively short period of vegetative growth. According to Haberlandt (1914, p. 183) and others, the intercalary regions remain "permanently meristematic"; that is, after the shoot has reached its mature length through the activity of the apical and intercalary meristems, the bases of the leaves and of the internodes can elongate further because of the special characteristics of the intercalary zones.

The present observations on the manner of growth of the shoot apex in *Zea* agree essentially with Sharman's (1942). In the youngest portion of the shoot the internodes as such do not exist; they develop through cell division at the base of the leaf-insertion disks. The insertions of the two superposed leaves are thereby separated from each other. In other words, the nodes are removed from each other by intercalary growth. The closeness of origin of two superposed nodes is emphasized by the common origin of the axillary bud of the lower leaf with the base of the next higher leaf. The axillary bud becomes separated from the upper leaf by the interpolation of the internode. The bud, then, according to Sharman, is associated with the internode of the leaf above and not with the leaf in whose axil it appears. Rösler (1928) has previously given the same interpretation of the origin of internodes and axillary buds in wheat. Similarly Evans and Grover (1940) concluded that the bud of a grass develops at the base of a "phytomer" (the unit of structure of the shoot composed of an internode, the leaf at its upper end, and the bud at its lower end) in the axil of the leaf that crowns the "phytomer" next below.

As Sharman has shown, the internode grows by orderly transverse divisions giving rise to longitudinal files of cells. Plate 10 illustrates this phenomenon. The longitudinal section depicted in this plate passed through two nodes (*n*) and one internode (*in*) between the bases of two leaves (*lb*), which were approximately the sixteenth and seventeenth from the apex. The nodes are characterized by the complexity of their vascular systems, but the young internode is composed of longitudinal

files of parenchyma (rib meristem) and of vertical strands of vascular tissue. This internode is in a state of division throughout its length. Later, the meristematic activity becomes confined to the base of the internode (Sharman, 1942). The leaf elongates similarly by intercalary growth, during which the cell divisions are gradually localized in the intercalary-meristem zone of the leaf sheath.

Whether represented by the young internode (or leaf sheath) or by a restricted region in the elongated internode (or leaf sheath), the intercalary "meristem" is a partly differentiated tissue region. Its degree of differentiation varies during the different stages of development of the organ containing it. As the internodes elongate, the dividing parenchyma cells of these regions show increasing vacuolation, and the vascular bundles differentiate through them. The vascular strands passing through the growing internode in plate 10 had mature protoxylem and protophloem. After the shoot parts have elongated, the metaphloem and metaxylem mature. Most parts of the plant become structurally rigid: the last vessels develop pitted walls, the bundle sheath is sclerified, and the hypodermal sclerenchyma forms its thick lignified walls. The final elaboration of the intercalary zones occurs, however, in relation to the retention of meristematic potentialities in these zones. The vascular bundles show a small amount of lignified tissue; and the vessels are of the annular and spiral types, these vessel types being directly continuous with pitted elements above and below. (This observation was reported by Strasburger, 1891, and is confirmed in the present study.) The bundles are not encased in a sheath of lignified cells, but are accompanied by a collenchymatous tissue in the form of massive sheaths or bundle caps. No lignified hypodermal sclerenchyma is formed.

Artschwager (1925) describes similar modifications of bundles in the intercalary-meristem regions in the sugar cane and gives further details on the variations in the structure of a grass bundle in the different parts of the shoot.

*The Leaf-Blade Bundles.*—The vascular bundles in the flat part of the leaf blade can be divided roughly into three groups according to size and structure. The largest (fig. 2, E) have a lignified sheath confluent with the hypodermal sclerenchyma. The sheath cells on the flanks of the bundle are shaped like elongated parenchyma cells and contain abundant large chloroplasts. In figure 2, E, the plastids are indicated by stippled circles. The uniseriate sclerenchymatous sheath layers on the xylem and phloem ends of the bundle (confluent with the hypodermal sclerenchyma) are free of chloroplasts. The bundle in figure 2, E, has two large lateral metaxylem vessels. Below these is an annular protoxylem vessel, which appears like a space because it is much extended

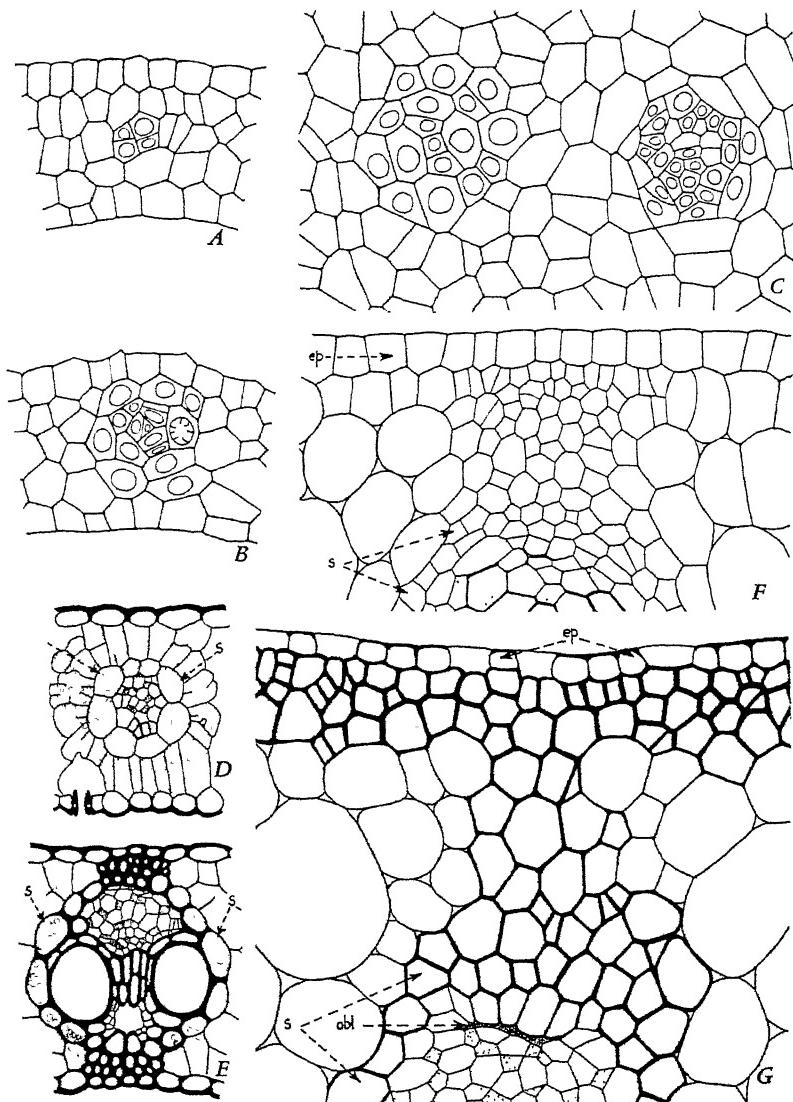


Figure 2.—*A* to *C*, Transverse sections from leaf (*A*, *B*) and stem (*C*) depicting early stages in procambial differentiation. The nuclei visible in these sections are indicated only in the cells that were concerned with the formation of the procambium. *D* and *E*, Transverse sections of mature vascular bundles from a leaf blade. The small cells indicated by stippling are companion cells; the stippled circles represent the chloroplasts. *F* and *G*, Transverse sections of portions of leaves illustrating two stages in the differentiation of the adaxial part of the bundle sheath and of the hypodermal sclerenchyma. *F* was taken from the same section as plate 5, *B*; *G* from the section as in plate 9, *B*. In *F* the entire visible part of the phloem is stippled; in *G* only the companion cells. Details are: *ep*, epidermis; *obl*, obliterated protophloem; *s*, sheath. (*A* to *C*, *F* and *G*,  $\times 467$ ; *D* and *E*,  $\times 160$ .)

longitudinally and because the ringlike thickening does not occur in this section. The metaphloem shows the usual composition (sieve tubes and companion cells), and the few protophloem elements appear as flattened cells between the metaphloem and the sheath. According to Cheadle (1942), the presence of vessels in leaf bundles is characteristic of the Gramineae.

The smallest bundles have entirely parenchymatous sheaths rich in chloroplasts (fig. 2, *D*). The walls of the sheath cells are somewhat thicker than those of the mesophyll, but are not lignified. According to Strasburger (1891, p. 336), the sheath cells of the small leaf bundles have cutinized radial walls. The xylem and phloem are much reduced in amount as compared with the large leaf bundles. Strasburger describes the tracheary elements as reticulate-pitted vessels (1891, p. 337, "vessel-like tracheids"). The vascular tissues of these bundles mature after the elongation of the leaf and are here interpreted as metaphloem and metaxylem.

The bundles intermediate in size between the largest and the smallest have parenchymatous sheaths. A hypodermal sclerenchyma strand occurs between the epidermis and the sheath—usually on both sides of the bundle, but sometimes on only one side.

The longitudinal strands of the leaf blade are interconnected by transverse anastomoses. In structure these resemble the smallest longitudinal strands. They contain tracheids (Strasburger, 1891, p. 338) and sieve tubes, and are enclosed in a chloroplast-containing parenchyma sheath. According to Strasburger, sieve tubes are absent in the smallest strands. Similar transverse bundles occur in the sheath (fig. 1, *C*, at *a*).

The midvein contains many bundles, the largest resembling the leaf-sheath bundles in size and structure.

#### ONTOGENY OF THE VASCULAR BUNDLE

*Initiation of the Procambium.*—The ontogenetic details are discussed with reference to the largest leaf-sheath and stem bundles that appear in mature state, such as the bundle in plate 9, *B*. One may follow conveniently the different stages in the development of the vascular strands by comparing the bundles in leaves of different ages as seen in transverse sections through a shoot apex (fig. 1, *A*, and plate 1).

Sharman (1942) has recently described the origin of leaves and the order of appearance of the procambial strands in *Zea*. Briefly, the leaf formation passes through the following stages: Periclinal divisions in the surface and subsurface cells at the base of the apical cone initiate the leaf buttress. Because of the two-ranked leaf arrangement these

divisions first occur above and opposite the median part of the next lower leaf. From here the divisions spread laterally around the base of the apical cone to form the encircling leaf base. Before completion of this lateral growth, the small protrusion below the apical cone formed by the first divisions begins to grow upward. Thus apical growth and lateral expansion combine to produce a structure that is highest at the point of its origin and that slopes down along the margins, which are in process of encircling the axis. The two margins advancing toward each other first meet (leaf 4 in plate 1), then overlap (leaves 5 to 9 in fig. 1, A, and plate 1). In the early stages of leaf development no boundary is evident between the leaf sheath and the lamina (Sharman, 1942). The following discussion of the procambial initiation will simply use, therefore, the word *leaf*. Plate 1 illustrates the nature of these leaves as seen in transverse sections.

Before the primordium completes the encircling of the apical cone and when its median part is about 30 to 40 microns high (this was leaf 1 in the shoot used in plate 1), a central procambial strand appears within the primordium. As the young leaf expands laterally, successive procambial bundles differentiate to the right and left of the median. (Compare the leaves of different age in figure 1 and plate 1.) The median and the first series of laterals are, for convenience, classified here as bundles of the first rank or first order (fig. 1, D), since, as a group, they arise first and become the largest in the leaf. Eventually bundles of the second rank are interpolated between those of the first (leaves 7 and 8 in fig. 1, A). Then appear bundles of the third rank (leaves 9 to 14 in fig. 1) and those of the fourth (leaf 14 in fig. 1). Still smaller bundles may be formed (Strasburger, 1891). During the formation of the smallest longitudinal strands, transverse anastomoses arise in the leaf (leaf 14 at a in fig. 1, C'). According to Sharman (1942), the median and the large lateral bundles differentiate acropetally within the leaf, whereas the bundles of higher ranks differentiate basipetally and appear at the apex after the laterals reach their highest position. The transverse anastomoses arise after the small longitudinal bundles. These also are formed in basipetal succession (Sharman, 1942). The order of appearance of the smallest bundles is related to the basipetal maturation of the leaves—a characteristic very common among angiosperms.

As shown by transverse and longitudinal sections of the developing leaves, the epidermis is continuous over the leaf margin, and marginal initials add new cells to this tissue layer. Submarginal initials give rise to all the other cell layers of the leaf. Sharman (1942, p. 251) suggests that the dermatogen also may add cells to the inner layers. The earliest (that is, the largest) bundles are initiated when the leaf is five layers

of cells in thickness. The first divisions indicating the beginning of such a bundle occur in the median of the five layers (fig. 2, A). First one cell divides; then adjacent cells become involved. The first division of the first cell may be anticlinal, followed by periclinal or oblique divisions of the daughter cells (fig. 2, A); or the opposite sequence may occur. Figure 2, B, and plate 2, A, show the median procambial strand from leaf 2 of the shoot used for plate 1. The two illustrations were taken from two sections 10 microns apart. In the center of the strand is a group of six small cells that resulted from a recent subdivision of three cells. This group could have arisen from one cell. Certain adjacent cells have also divided or were about to divide around the periphery of the group of small cells. Thus the early divisions initiating a procambial strand appear to spread from a center, the latter being formed by the cells that had divided first. The cells around the central group have a tendency to divide and to elongate tangentially with respect to this group (fig. 2, B, and plate 2, A). The products of these divisions become further subdivided by walls of different orientation, but mostly anticlinal with respect to the periphery of the bundle (plate 2, B).

Depending on the size of the bundles, the centrifugal growth of the procambial strands through the addition of cells on its periphery may be smaller or greater. According to Potonié (1886) and the present observations, the extremely small bundles forming the cross connections in the leaves arise entirely within a layer one cell deep and one cell wide.

While the addition of cells occurs on the periphery of the bundle, the cells within it also divide. Since these early divisions are followed by little cell enlargement, the resulting procambial cells are smaller than those from which they arose. Figure 2, C, shows graphically the difference in the size of cells at the beginning (bundle to the left) and at a later stage (bundle to the right) of procambial differentiation.

In longitudinal views the procambial cells at a given level of a strand tend to be of the same length, with the transverse walls placed at the same levels. This gives the procambium a storied appearance. The youngest procambial cells are as long as the adjacent parenchyma cells, but rapidly become longer.

After the procambium has thus been organized into strands of narrow elongated cells (plate 2, B, bundle to the left), further divisions within the strands increase their thickness in the radial and tangential directions. Since now the cells enlarge somewhat after each division, the size of the procambial cells is not further diminished. When first differentiated the procambium is, as usual, more densely cytoplasmic than the adjacent parenchyma because of the delayed vacuolation in the procambial cells (plate 2, B, bundle to the left). After differentia-

tion of the first vascular element (a sieve-tube element) begins, the procambial cells progressively vacuolate. (Compare the successively older bundles in plates 2, *B*; 3, *A*; and 4, *A*.)

The divisions preceding the differentiation of the first sieve tube within the procambial strand are concerned mainly with the radial increase of bundle thickness; that is, they are periclinal with respect to the leaf or stem surface. The cells assume, therefore, a somewhat orderly arrangement, tending toward a radial alignment (plate 2, *B*, bundle to the right; plate 3, *A*). Occasional anticlinal divisions cause the bundles to expand laterally. As the procambial strands increase in circumference, the adjacent parenchyma cells respond by increasing their diameters parallel to the surface of the bundles and by dividing anticlinally to this surface. Occasional periclinal divisions also occur (plates 3, *B*; 4; 5, *A*). Because of these divisions the parenchyma cells around a young bundle appear transitional in size between the cells of this bundle and the parenchyma farther removed.

Since the bundles of different ranks are initiated at successively later stages of leaf development, the later strands appear in more obviously vacuolated leaf sections than the earlier. The bundles of the first rank are formed within the rather meristematic leaf tissue. Leaf 4 in plate 1, for example, shows the first three procambial strands within the still densely cytoplasmic median portion of the leaf. The successive bundles of the first order are initiated closely behind the marginal meristem, as one sees on examining the overlapping meristematic margins of leaves 5 to 7 in plate 1. The smaller strands (bundles of second, third, and fourth orders) are formed by subdivisions of conspicuously vacuolated cells. (Note the high degree of vacuolation of the median portions of leaves 6 and 7, plate 1, in which the bundles of second rank are initiated.) Similarly in the stem, the first and largest traces arise near the apex in a more densely cytoplasmic tissue than the smaller, later bundles. The small horizontal bundles of stem nodes (fig. 1, *D*) and the transverse connections in the leaves appear among the latest in their respective organs, and the vacuolation of the cells that become subdivided in the process of their formation is most conspicuous.

The bundles of successive ranks, within the midrib and sheath, seem to arise successively closer to the abaxial side of the leaf (plate 3, *B*). Actually they all are initiated in the second layer of cells from the abaxial epidermis. The apparent extreme peripheral origin results from the increase in thickness of the median leaf portions through adaxial meristematic activity. Eventually, because of the repeated periclinal divisions, the adaxial periphery of the median part of the leaf appears like a cambium in transverse sections (leaves 6 and 7 in plate 1).

*Protophloem and Protoxylem.*—As already mentioned, the large bundles are initiated before elongation of the organs in which they occur. Certain phloem and xylem elements (the *protophloem* and the *protoxylem*) mature during this elongation and, as is commonly known, become destroyed before the leaf or axis attains its mature size. Though in the xylem the longitudinal stretching appears to be the main cause of destruction of the conducting elements, the protophloem is obliterated even if longitudinal growth is little pronounced. Thus, according to Strasburger (1891) and the present observations, in the nodes of *Zea* the protoxylem of the large bundle is not converted into a lacuna, but the protophloem is crushed.

The successive stages in protophloem and protoxylem differentiation may be followed in plates 2, *B*, and 3 to 5. Shortly after the procambial strand is delimited, a sieve-tube element is evident near the outer periphery of the strand. In plate 2, *B* (bundle to the right), this sieve-tube element is immature. Though its walls are already somewhat thick and deeply stained, the cytoplasmic contents are still as dense as in the procambial cells. The first sieve tubes in plate 3, *A*, are mature. Their thickened walls and the lack of stainable cell contents make them very conspicuous. Additional protophloem sieve tubes differentiate centripetally from the first, eventually forming a compact cluster of "clear" cells near the outer periphery of the bundle (plate 5, *A*). They are bordered by the young sheath cells on the outside and by the procambium on the inside.

The protophloem sieve tubes lack companion cells. They are enucleate in the mature state and have well-developed sieve plates. Their nacré walls (Esau, 1939), though only moderately thick in paraffin material, are thicker than the procambial walls (plate 5, *A*). Plate 6, *A*, shows parts of the somewhat stretched protophloem sieve-tube elements in a longitudinal view (the two lower cells marked with *st*). The inclined end wall to the right (*sp*) bears a sieve plate, discernible as such under an oil-immersion lens. In this figure the thickness of the walls and the thinness of the protoplasts are obvious. As the protophloem ages and is stretched, the walls become noticeably thinner (plate 5, *B*). Plate 7, *A*, shows part of an old protophloem sieve tube in longitudinal view (the upper cell marked *st*). Since its elements are very long, the transverse walls do not appear in this section; the longitudinal walls are very thin, in sharp contrast to those of the adjacent differentiating metaplhloem sieve-tube elements (the lower cell marked *st*).

The destruction of the protophloem is depicted in plates 7, *B*, and 8. The thin-walled protophloem sieve tubes are still intact in plate 7, *B* (two of the outer layers of cells marked *st*). The sheath cells (*s*)

immediately outside the protophloem have divided periclinally. Their subsequent enlargement, combined with the centrifugal growth of the metaphloem, causes a crushing of the protophloem. The first stage in this process is discernible in plate 8, *A*; the second in plate 8, *B*. The final stage of protophloem obliteration appears in plate 9 (at *obl*). In old stem parts the obliterated protophloem shows a strong lignin reaction with phloroglucinol and hydrochloric acid.

When two to three protophloem sieve tubes are mature, the first protoxylem element differentiates. The nature of this and of the subsequent protoxylem elements was determined on the basis of their appearance during development. When the differentiating tracheary elements show secondary thickenings on the longitudinal walls, the entire or most of the transverse end wall—the part which is removed just before maturation—remains free of secondary thickenings and is deeply stained. Since the transverse wall is thicker in the middle, it appears somewhat lenticular in shape in the narrowest elements. Because these developmental stages resemble those observed in the differentiating vessel elements of other plants (Esau, 1936b; Esau and Hewitt, 1940), the tracheary protoxylem elements in *Zea* are here interpreted as vessels.

Cheadle (1942) has pointed out that in the mature state the spiral xylem elements of the Gramineae cannot well be studied in macerations; they are too much stretched and too difficult to separate from other cells. Cheadle, however, identified spiral vessels in at least one plant organ in twenty-two species of grasses. In the metaxylem, vessels were found in all organs of forty-five species of thirty-three genera of Gramineae.

The first protoxylem vessel is usually annular and appears near the inner margin of the bundle (plate 4, *A*). Before the first vessel matures, the xylem end of the procambial strand becomes rather more vacuolated than the phloem end (plate 3, *A*). Later the phloem region also vacuolates conspicuously (plate 4). The first and the subsequent protoxylem vessels appear, one after the other, in the same radial row of cells, each successive element being wider than the preceding. (Compare the bundles in plates 4 and 5.) During differentiation of the protoxylem the storied appearance of the procambium is disturbed. While the mother cells of the earlier vessels are elongating, those of the later vessels are still dividing by transverse walls, so that the end walls of the successive vessel mother-cell series occur mostly in different horizontal planes. Plate 6, *A*, shows, above, a portion of a mature annular protoxylem vessel whose segments are longer than the width of the photograph. Then follows a series of vessel mother cells, considerably expanded, but

rather short. Transverse divisions have been completed in this series. The end walls already show the characteristics of vessel end walls before dissolution (Esau, 1936b; Esau and Hewitt, 1940). The mother cells of the third series are little expanded and are very short. Obviously this series was still dividing by transverse walls when such divisions ceased in the second series.

The radial alignment of cells in the protoxylem end of the bundle (plates 5, *B*, and 9, *B*) is disturbed by the expansion of the protoxylem vessel segments and by the occurrence of anticlinal and oblique divisions in the adjacent cells. The small cells in this part of the bundle remain parenchymatous (the protoxylem parenchyma).

As previously mentioned, the conducting elements of the protoxylem are destroyed during elongation. When the first vessels are stretched they disappear from view completely, except where a ring happens to occur in a section. Seemingly, in the early stages of this process the parenchyma cells crush the xylem elements. In dicotyledons the xylem parenchyma commonly obliterates the stretched protoxylem cells (Esau, 1936a). In *Zea* and other grasses, after several vessels are destroyed, a lacuna is formed because the adjacent parenchyma does not fill the space formerly occupied by the vessels.

The protoxylem vessels mature one after the other and are also stretched successively. Plate 4, *A*, shows a protoxylem vessel before stretching. Every section of the bundle showed a ringlike secondary-wall deposit, because the rings were still close together. In the bundle in plate 4, *B*, the ring appears somewhat tilted. When the rings become widely spaced many sections lack rings (plate 5, earliest xylem elements in both bundles). At this time the younger vessels still have closely arranged rings or spiral coils.

*The Metaphloem and Metaxylem.*—As shown earlier, the periclinal divisions and the radial seriation of cells resulting from these divisions become evident in the procambial strands before the first conducting elements mature (plate 2, *B*, bundle to the right). This method of cell division continues during the following stages of bundle differentiation. As the cells increase in number, the orderly arrangement of the procambial cells becomes more and more conspicuous (plates 4 and 5). The periclinal divisions occur in several cells of one radial row. In other words, there is no single initial layer like the one commonly thought to occur in the cambium. Nevertheless, in the last stages of cell addition the procambium, as seen in transverse sections, markedly resembles the cambium of the dicotyledons. The dividing cells become limited to a narrow region, and the immediate products of division have short radial diameters (plates 5, *B*; 7, *B*; and 8). The radial

arrangement of cells is later somewhat obscured in metaxylem—as in protoxylem—by enlargement of vessels, though the small-celled part of the metaxylem may remain in orderly arrangement (plate 9, *B*). The mature metaphloem reveals by its pattern the origin from a radially seriated meristem (plate 9).

Plates 7, *B*, and 8 show the differentiation of the metaphloem. The metaphloem sieve tubes have companion cells. As usual, these cells arise from the same phloem mother cells as the sieve-tube elements with which they are associated. A longitudinal division of the phloem mother cell forms a wide and a narrow cell (plate 7, *B*, and 8, *B*). The narrow cell divides again, at right angles to the first plane of division of the phloem mother cell, so that a vertical file of companion cells is formed in connection with each sieve-tube element. The protoplasts of the differentiating companion cells become denser than those of the cells from which they arose (plates 6, *B*; 7, *B*; and 8, *B*).

After the division of the phloem mother cell into the companion cells and the sieve-tube element, the walls of the latter become conspicuously thickened except on the side touching the companion cell (plate 7, *B*). This, the so-called "naeré" wall (Esau, 1939), appears before the nucleus disintegrates (plate 8, *B*, sieve tube with a nucleus, *n*, and a thick wall; plates 6, *A*, and 7, *A*) and shows prominent pit areas (plate 7, *A*, indentations in the thick wall of the lower cell marked *st*). The pit areas become sieve areas (Cheadle and Whitford, 1941); the transverse or slightly oblique end walls differentiate as sieve plates. Plate 9, *A*, shows at the left (above) a mature sieve plate, in which the lighter dots represent the callus cylinders lining the pores. At this magnification the cytoplasmic connecting strands through the callus cylinders are not discernible.

The early metaxylem vessel that occurs to the left of the lacuna in plate 9, *B*, usually begins to differentiate while the organ elongates and shows the effect of this growth in the considerable length of its segments. The two lateral metaxylem vessels are initiated later, are little affected by stretching, and have therefore comparatively short segments. According to Frey-Wyssling (1940), the reduction of the segment length of the last metaxylem vessels, as compared with the earlier vessels, distinguishes *Zea* and other Gramineae from the dicotyledons with secondary growth, in which the metaxylem elements are progressively longer.

**The Bundle Sheath.**—The foundation of the bundle sheath is laid during the early stages of procambial differentiation. The outermost layer of cells in the bundles of plates 2, *B*, 3, and 4 is a bundle sheath in its earliest stage of development. The young sheath follows the increase

in circumference of the bundle by anticlinal divisions (anticlinal with respect to the periphery of the bundle). Then on the xylem end of the strand the sheath becomes two- to several-layered by periclinal divisions (plates 5, B, and 9, B). On the flanks also the sheath may be more than one cell thick. In the first stages of bundle development the sheath is uniserrate outside the protophloem (plates 3, B, and 4). Later, divisions occur within, and also outside, the original sheath layer (plate 5). The cells resulting from the divisions outside are also added to the sheath.

The amount of sheath tissue added to the bundle in its somewhat advanced stage of development varies with the size of the bundle and its location in the plant. Most massive sheaths develop in the intercalary-meristem region. These are the collenchymatous sheaths (or bundle caps) discussed previously. The compound bundles in this region strikingly illustrate the close developmental relation between the sheaths and the vascular tissues. They become compound through the development of additional small vascular strands within the sheath surrounding a larger bundle. Figure 3 illustrates this phenomenon. The vascular tissues at *a* were the first to differentiate. Cell divisions around this bundle produced the massive sheath. In the outer part of the latter, new vascular groups began to differentiate before the sheath matured into collenchyma. The small strand at *b* had three sieve tubes with companion cells (stippled cells) and a tracheary element, still immature but with secondary walls. In the bundle at *c* two sieve tubes with companion cells were present, and a tracheary element without secondary thickenings. The bundle at *d* showed only an incompletely expanded tracheary element. Although certain cell divisions had occurred around it, no phloem elements had yet differentiated.

The lack of developmental distinction between the sheath and the vascular tissues is revealed also by other bundles. Thus the first xylem element may differentiate from a sister cell of a young sheath cell; and in the small transverse anastomoses the vascular elements and the sheath cells arise from the same parenchyma cell. Then, of course, in the earliest stages of procambial initiation the future vascular cells cannot be separated from the future sheath cells (fig. 2, *A* to *C*; plate 2, *A*).

Similarly, there is no clear demarcation between the sheath and the adjacent tissues on a developmental basis. It has been shown that the procambial strand grows first by the addition of cells on the periphery through division of cells adjacent to the bundle. Often, after the last of these divisions, half of a cell is added to the bundle, whereas the other half remains outside. Then, as already mentioned, new sheath cells may be added to the bundle in the later stages of its development.

The lack of demarcation between the bundle sheath and the adjacent

tissue is most obvious in the bundles that are in contact with the hypodermal sclerenchyma in stem and leaves. This tissue is initiated at the time when the bundle sheath is being thickened by the division of cells located outside the protophloem end of the bundle. The hypodermal sclerenchyma originates by longitudinal divisions of the parenchyma

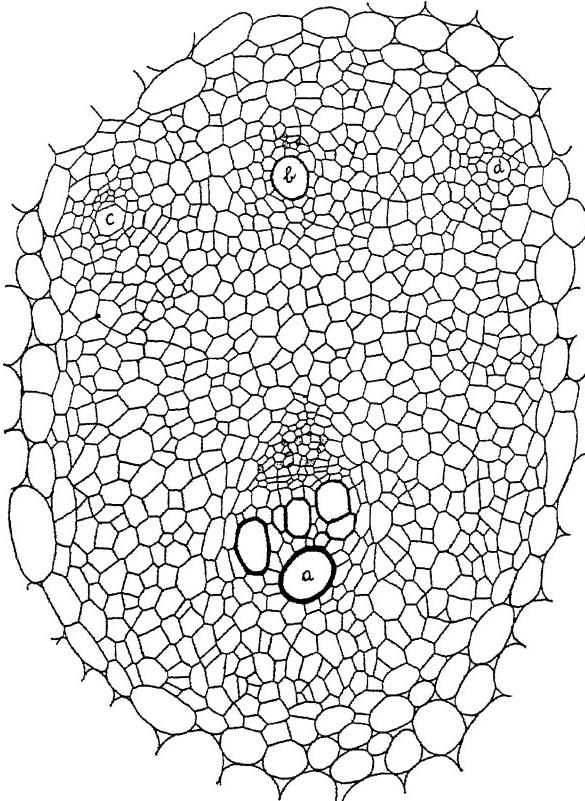


Figure 3.—Transverse section of an immature bundle from the intercalary-meristem region of a leaf sheath. This bundle is a compound structure. Four vascular strands (*a* to *d*) are imbedded in a comparatively small-celled tissue, which at maturity becomes collenchymatous. The vascular strands are in different stages of development, that in *a* being the most advanced and that in *d* the least differentiated. (x 228.)

underlying the young epidermis. In the narrow part of the leaf blade the superficial layer of cells also contributes to this sclerenchyma; in other words, some of the sclerenchyma cells are sister cells of the epidermis. The protodermal origin of peripheral sclerenchyma strands has been previously observed in the monocotyledons (Haberlandt, 1914, p. 203-04). Figure 2, *F*, illustrates an early stage of development of the

sheath and of the hypodermal sclerenchyma in connection with the bundle that appears in its entirety in plate 5, *B*. The epidermis is not involved in the production of this hypodermal sclerenchyma strand. A similar region in a mature state is depicted in figure 2, *G*, prepared from the same section as plate 9, *B*. The sheath and the hypodermal sclerenchyma are connected by a narrow strand composed of sclerenchymatous cells similar to those of the sheath; the hypodermal sclerenchyma has somewhat thicker walls. The epidermal cells adjacent to the hypodermal fibers are flatter than elsewhere (fig. 2, *E*), even if the protoderm does not contribute cells to the sclerenchyma. It appears as though the cell multiplication which occurs during the formation of the bundle cap and the hypodermal sclerenchyma produces a pressure beneath the epidermis so that the cells of the latter do not expand radially. Plate 6, *A*, shows in longitudinal view the region between the protophloem sieve tubes and the epidermis of the leaf containing this protophloem (the upper of the two layers of cells labeled *ep*). The young sheath cells and the differentiating hypodermal sclerenchyma cannot be distinguished from each other.

If the bundle is closer to the periphery of the leaf than the bundles in figure 2, *F* and *G*, the merging of the bundle sheath and the hypodermal sclerenchyma is complete. If the bundle is somewhat farther away, narrow elongated cells with thin cellulose walls intervene between the two tissues. Finally, the hypodermal sclerenchyma may be completely dissociated from the bundle.

*The Stage of Bundle Differentiation as Related to the Order of Leaf Origin at the Shoot Apex.*—Sharman (1942) has related the anatomical development of *Zea* leaves to the order of their origin at the apex. Since the shoots used in the present study showed a much slower differentiation than the material described by Sharman, the data are presented for comparison.

This paper will not discuss the longitudinal order of differentiation of the vascular system. The writer agrees, tentatively, with Sharman (1942): the median procambial strand and its protophloem differentiate acropetally from the axis into the leaf; and the large lateral bundles are clearly evident when they first appear at the base of the leaf, though they cannot be distinguished at lower levels. Sharman concluded that the lateral strands differentiate basipetally into the axis and acropetally into the leaf from somewhere near the base of the leaf. He also assumes that the median strand has a basipetal course in its lower parts within the stem. His view on the developmental course of the smallest bundles has already been given.

Using as an example the shoot partially depicted in figure 1, the

comparative degree of differentiation of the vascular tissues in the different leaves is as follows:

The shoot was cut consecutively through thirteen internodes. The fifteenth and eighteenth nodes were cut separately. In the latter the long and the short diameters of the axis were 10 mm and 8 mm respectively. Leaves 1 to 6 were 0, 70, 250, 570, 970, and 1,640 microns high, respectively; the node-to-node distances between the nodes 1 and 14 (at these levels the internodes were not differentiated as such or could not be distinguished in cross sections) measured 50, 50, 80, 80, 80, 80, 100, 160, 240, 270, 520, 500, and 900 microns. Leaf 1 was just initiated, and only the median part of its buttress was discernible, whereas leaves 7 to 13 were cut below their apices. In the shoot of plate 1 the first leaf was a few microns high.

The procambial strand of leaf 1 could be discerned only in the axis (fig. 1, A). Leaf 2 had the median procambial strand in its base. The median strand of leaf 3 reached to 60 microns below the leaf tip; and the laterals were evident at the base of the leaf, but not in the axis. The traces of leaves 2 and 3 had mature sieve tubes. At a level similar to that in plate 1, the median strand of leaf 4 resembled the bundle shown to the left in plate 2, B. Farther below, an immature sieve tube occurred, whereas the trace contained mature phloem elements. The median strand of leaf 5 had reached, at levels above figure 1, A, the stage of development depicted in plate 2, B, to the right; at lower levels the sieve tube was mature. The median bundle of leaf 6 had two sieve tubes and one xylem element like the bundle in plate 4, A, except that the xylem element was not yet mature. It had secondary walls, but the protoplasts were still intact. The secondary walls were evident 1,370 microns below the leaf apex and through several internodes in the axis. On each side of the median bundle were two bundles with one or two mature sieve tubes, but without xylem. Still farther toward the leaf margins followed three or four bundles with immature sieve tubes; then several procambial strands without vascular elements. Divisions to form bundles of second rank occurred in leaf 6 (plate 4, A, below).

Leaves 1 to 6, available in their entirety, had not yet ceased their apical growth, as was evidenced by the highly meristematic appearance of their apices. The marginal growth was still evident in leaf 11. These data strikingly contrast with those of Sharman (1942), in whose material plastochnone 6 was characterized by a fully expanded lamina with metaxylem and metaphloem forming basipetally in the sheath undergoing its final elongation, whereas the marginal meristems were becoming inactive in plastochnone 4.

The median strand of leaf 7 (the first that was cut below its apex)

of the present study had reached the stage of development depicted in plate 3, *B*, to the left. The xylem element was somewhat stretched in the median levels, but not above and below. On one side of the median strand were two bundles with two sieve tubes and one vessel each, the latter not yet stretched. Then followed a strand with an immature tracheary element and some sieve tubes. The others had no xylem. In about three more bundles, mature sieve tubes were present. On the other side of the median the bundle development reached almost the same stage, except that there was still no mature xylem.

The median strand of leaf 8 was somewhat younger than the bundle in plate 5, *A*. The first protoxylem vessel was noticeably stretched in the median levels available, but not in the upper sections and not at the insertion of the leaf. Bundles of the third rank in their initial stages of development occurred in the sections of leaf 8. The median of leaf 9 was somewhat larger than that of 8, having three mature protoxylem elements. At higher levels the first element had almost disappeared because of stretching and crushing, whereas the second was somewhat stretched. At the base of the leaf, which was noticeably more meristematic than the upper regions, the first element, though slightly stretched, was apparently still intact. The first xylem in the laterals was also somewhat stretched above.

Though the stretching of the first two protoxylem vessels was very pronounced in the median bundle of leaf 10 at higher levels, very little of it occurred below. In leaf 11 the fourth protoxylem vessel was differentiating acropetally; in leaf 12, the fifth. Both these leaves indicated considerable stretching of the first vessels at their bases. The median strands of leaves 10 to 12 showed the successive early stages of metaphloem and metaxylem differentiation (plates 5, *B*, and 7, *B*). This process was taking place in the basipetal direction, as indicated by the younger appearance of the bundles below. Particularly striking was the disappearance, toward the leaf bases, of the expanding lateral metaxylem vessels. Among the basipetally differentiating elements was also a centrally located vessel, which Sharman (1942) apparently called the last protoxylem. As was mentioned previously, judging by the time of its development it might also be called metaxylem. This central vessel had secondary walls and intact protoplasts above in the median strand of leaf 13. Farther down, the secondary walls were absent; and at the base of the leaf all evidences of metaxylem differentiation had disappeared. Of the five acropetal protoxylem vessels previously formed in the median strand of leaf 13, four were much stretched above and were associated with a lacuna. In fact, the number of vessels involved in the formation of the lacuna could not be established at the upper

levels, so pronounced was the rupture of the first three. At the base of the leaf, however, all five vessels were intact, though the first two were much stretched. The first bundles of the second rank had mature sieve tubes in leaf 11; those of the third rank in leaf 13.

The central basipetal vessel was mature above in leaf 14; farther down, the protoplasts were intact; and 650 microns above the union of the leaf with the stem the secondary walls had disappeared. A prominent

TABLE 1  
LENGTHS IN CENTIMETERS OF THE ASSOCIATED LEAF BLADES, LEAF SHEATHS,  
AND INTERNODES OF A VIGOROUSLY GROWING *ZEA* SHOOT; AND CERTAIN  
BUNDLE CHARACTERISTICS OF THE INTERNODES\*

Leaf and internode number†	Leaf blade	Leaf sheath	Internode	Certain bundle characteristics of the internodes
1 . .	67	1 2	0 4	First protoxylem elements mature
2 . .	80	2 0	0 8	No protoxylem lacuna
3 . .	100	4 0	1 0	Lacuna barely indicated
4 . .	110		2 0	Metaphloem and metaxylem just initiated
5 . .	110		5 0	
6 . .	120	22 0	14 0	Lacuna formed, protophloem crushed, lateral metaxylem vessels still with nuclei
7 . .	120	24 0	22 0	Metaxytem mature, sheath immature
8 . .			21 0	Fully mature bundles
9 . . .			15 0	Fully mature bundles
10 . . .	...	.	6 0	Fully mature bundles

\* Data adapted from Strasburger, 1891.

† Leaves and internodes are numbered consecutively beginning with the youngest; no. 10 is the lowermost on the stem.

lacuna appeared in the place of the first four vessels at higher levels. The fifth vessel was intact. The basipetal central vessel occurred in the same radial row as the acropetal vessels and was in lateral contact with the fifth protoxylem vessel. Below, near the leaf insertion, at least three of the acropetal protoxylem elements were intact. Here the lacuna was absent. The expansion of the central and of the lateral metaxylem vessels had progressed to the base of the leaf.

At higher levels of leaf 15 all the bundles were mature, those of the first rank appearing like the bundle in plate 9, B. Toward the base, however, part of the metaphloem was still immature, the lateral metaxylem vessels had no secondary thickenings, and the sheath had thin, non-lignified walls. The lowest part of leaf 15 was not available, but the next larger leaf showed at least three intact protoxylem vessels in the median bundle. Finally, leaf 18 showed at the very base the stages of final development of bundles characteristic of the "adult" intercalary meristem. One of the smaller lateral bundles from this region appears in figure 3. The collenchyma is not yet thickened, and the metaxylem not

yet fully mature. The median bundle showed two intact protoxylem elements, secondary walls and protoplasts in the metaxylem vessels. The metaphloem was almost mature.

As Sharman (1942) has explained, the basipetal maturation of the metaxylem and metaphloem within the leaf is related to the long-delayed intercalary elongation of the leaf sheaths. The relatively slow development of the sheaths is evident from Sharman's (1942, p. 248) table 1 and from Strasburger's (1891, p. 357-61) data. The latter are summarized as table 1 in the present paper. The internodes attain their mature length still later than the sheaths; and the maturation of the vascular bundles in the internodes occurs, as in the sheaths, after their elongation (column 4 in table 1; also Sharman, 1942).

The picture obtained from all these data is as follows: Before and during the elongation of the shoot, the protoxylem and protophloem form connections between the growing organs and the mature parts of the plant. After the elongation, the metaxylem and metaphloem are formed. These tissues mature first in the leaf blade, because it attains its mature length first; then their differentiation progresses through the leaf sheath into the internode, maturing in these organs after they complete their intercalary growth. The bundle sheath matures in the same direction. The special characteristics of the bundle sheath and metaxylem of the intercalary zones of the leaf sheaths and internodes make possible a further, probably limited elongation of these organs.

The continuity of the vascular tissues across the growing regions is maintained, presumably, through the relative structural plasticity and developmental adjustments of the protophloem and protoxylem. The elements of these tissues are capable of some extension in the mature state without, apparently, being destroyed. With further stretching they are destroyed, but the protoxylem (and protophloem) elements differentiate one after the other and are destroyed in a similar succession. Such method of growth would seem to provide some intact elements during the entire period of elongation, until afterwards the metaxylem and metaphloem mature in the completed internode and sheath.

Sharman (1942, p. 274) assumes, however, that when the protoxylem is ruptured in the elongating organs the leaf has no direct connections with the stem by means of differentiated water-conducting cells and that therefore the water must move part of its way across living cells. Sharman's own data do not prove this point. One might surmise that in table II (Sharman, 1942, p. 268) leaf 6 illustrating the basipetal differentiation of the metaxylem is left without xylem elements between levels 34 and 37. His text figure 21 (p. 270), however, indicates the presence of intact protoxylem at both these levels. The condition of the

xylem in the remaining 4 cm of this leaf is not mentioned. Similarly, in all other illustrations, immature metaxylem is associated with some intact protoxylem in the same bundle.

In the present writer's experience, eosin solution passes readily through the elongating internodes and leaf sheaths of *Zea* and other grasses, just as it would pass through open water-conducting channels. Under the dissecting microscope the stained bundles appear entirely continuous and (in material stained with phloroglucinol and hydrochloric acid) show some mature water-conducting elements in sections taken at different levels; metaxylem elements at the higher, more mature regions of the leaf; and protoxylem elements in the growing zones. The data obtained from the paraffin sections, given earlier in this paper, also indicate continuity of the conducting channels across the active intercalary meristems. Further studies using a wide range of material would be desirable to test the value of Sharman's assumption.

#### DISCUSSION

In the present paper the terms *protophloem* and *metaphloem*, *protoxylem*, and *metaxylem* are used in the sense in which they were originally conceived and in keeping with the writer's views as previously expressed (Esau, 1943). In this classification of the primary vascular tissues the relation of their development to that of the organ or plant as a whole is more important than their morphological characteristics. Thus employed, the concepts of *protophloem* and *metaphloem*, *protoxylem* and *metaxylem* serve the distinctly useful purpose of giving a dynamic picture of plant structure and of clarifying the relation between the development of the plant and the function of the vascular system. The protophloem and the protoxylem are quickly initiated in the shoot apex and (through their relative structural and developmental plasticity) maintain the continuity of the conductive channels in the growing regions. The less plastic but more elaborate metaphloem and metaxylem assume the function after the plant organs reach their mature size. Though the statement above consists of well-known facts, the repetition seems justified in view of various recent attempts to re-evaluate the categories of the primary vascular tissues, to give them new meanings, or even to discard the classification entirely—all on the basis of very limited morphological or developmental facts. (See review by Esau, 1943.)

Inidentally, the vascular bundles of *Zea* (and probably of other Gramineae) offer excellent class material to show the student the distinctive features of the successive parts of the primary phloem and primary xylem. In contrast to Stover's (1934) results, the present study

demonstrates a rather clear distinction between the protophloem and metaphloem of *Zea*.

The present investigation bears upon the problem of the developmental relation between the bundle sheaths and the vascular tissues of the Gramineae. These sheaths obviously develop as integral parts of the vascular bundle. Similarly related to the vascular tissues from the developmental standpoint are all the different types of sheaths in *Zea*—that is, the parenchymatous sheaths of the small bundles within the leaf blade, the sclerenchymatous sheaths of the large and small bundles in the other parts of the plant, and finally the collenchymatous sheaths in the intercalary region. The compound bundles of the intercalary zone show in a most striking manner the close relation between the sheath and the vascular tissues: additional vascular strands develop within the bundle cap of an earlier, larger strand. Strasburger's (1891, p. 345) classification of all bundle sheaths in *Zea* as parts of the stele ("Stelolemmae") seems practical.

This classification involves, however, some difficulties. The bundle sheaths, particularly the collenchymatous and the sclerenchymatous, cannot be sharply separated, on the basis of origin, from the adjacent parenchyma and from the sclerenchyma strands that do not constitute parts of the bundles. The similar origin and development of the intra- and extra-fascicular sclerenchyma illustrate Foster's (1942, p. 32) statement that "the nomenclature and classification of cell types and 'tissues' is still in a confused and uncertain state." Classifying the fibers, Foster (1942, p. 74) follows Haberlandt (1914, p. 152–55) in placing all the extracambial fibers into the group of "bast" fibers. The sclerenchyma of the monocotyledons also belongs in this category. As Foster states, this is a "topographical" classification; it is doubtless the most convenient at present. Haberlandt (1914, p. 199–202) goes even further in identifying the extra- and intrafascicular fibers by interpreting the meristem giving rise to the extrafascicular fibers as *procambium*. Plate 6, A, in the present paper shows how such a concept could be formulated: the procambium between the xylem and phloem displays the same morphology as the meristem between the protophloem and the epidermis that forms the bundle sheath and the extrafascicular hypodermal sclerenchyma. Further comparative developmental studies are needed before Haberlandt's use of the term *procambium* can be properly evaluated.

The procambium that gives rise to the vascular bundles in *Zea* shows a predominance of tangential divisions, a tendency most pronounced in the late stages of bundle development. This method of division causes a resemblance between the procambium and the cambium of the dicoty-

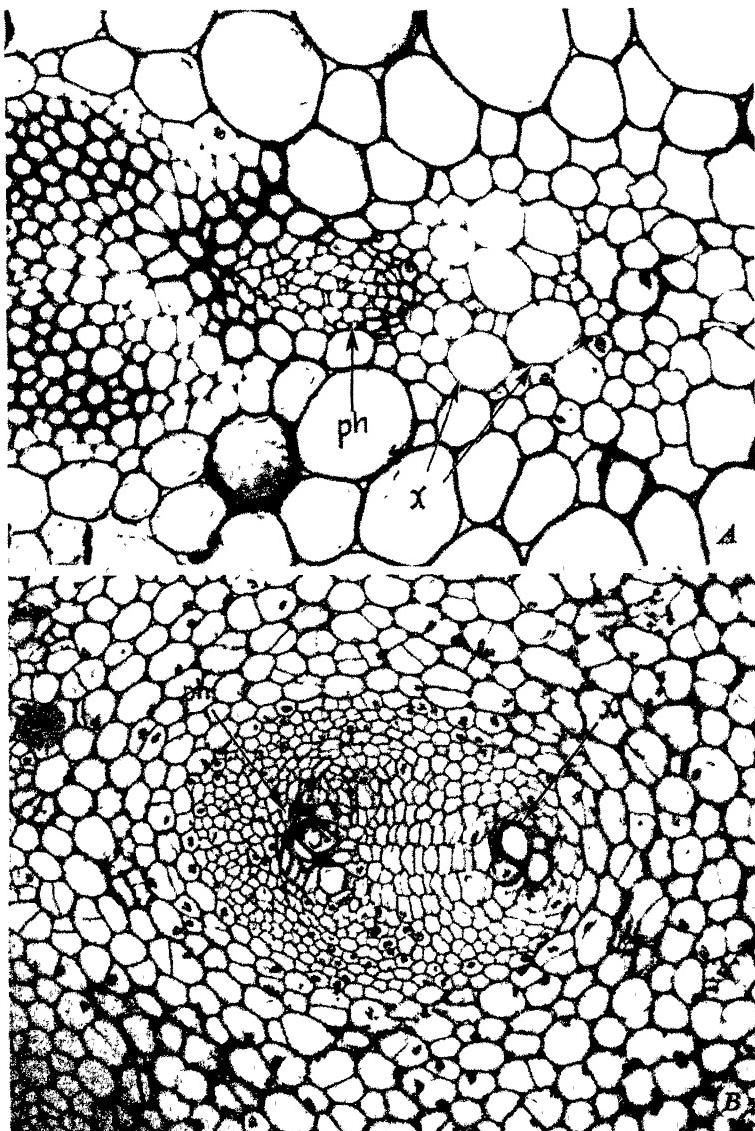


Figure 4.—*A*, Transverse section of a vascular bundle from a leaf of *Iris germanica*, showing the orderly radial seriation of the mature metaphloem (*ph*). The xylem (*x*) appears to the right of the phloem. *B*, Transverse section of a vascular bundle from a young leaf of *Cocos nucifera*, illustrating the cambiumlike appearance of the meristem that gives rise to the metaphloem and metaxylem. The protophloem (*ph*) and the protoxylem (*x*) are differentiated in this bundle. (Both  $\times 250$ .) (From slides lent by Dr. V. I. Cheadle.)

ledons as seen in transverse sections. The radial seriation of the procambium cells is very common in the monocotyledons. Thus figure 4, B, shows an immature bundle of a *Cocos* leaf, with orderly aligned meristematic cells between the protoxylem and the protophloem. The literature contains many more examples. (See review by Esau, 1943.) Sometimes the radial seriation is clearly maintained by the mature tissues, as in the instance of the metaphloem of *Iris* in figure 4, A. As previously emphasized (Esau, 1943), the problem of tissue classification has been only confused by the attempts of many workers (recently Sharman, 1942) to use the radial seriation of the meristematic cells as the principal criterion for distinguishing between the procambium and the cambium. A broad flexible classification, taking into consideration developmental aspects of the plant as a whole, has already been advocated by the writer in reference to the vascular meristems, as well as the vascular tissues (Esau, 1943). All the vascular tissues of *Zea* are here interpreted as primary and arising from procambium. These vascular tissues are a part of the wholly primary plant body. In certain arborescent monocotyledons the primary body is amplified by the addition of secondary tissues (mainly vascular).

Recently Moreland and Flint (1942, p. 361) interpreted the cross connections in the sheath of the sugar cane as secondary because "they arose from living cells that had become permanent and then returned to the meristematic condition." Modern morphologists of course regard living parenchyma cells (or, indeed, any living cell) not as "permanent," but as potentially meristematic (Hayward, 1938, p. 14; Bloch, 1941; Foster, 1942, Exercise III and p. 58; and others). Almost obsolete, therefore, is the distinction of the secondary tissues from the primary on the basis that the former arise from cells that returned to the meristematic condition. The present study, furthermore, by comparing the development of the cross connections with that of the other bundles, has revealed a whole series of transitions from the bundles of the first rank (formed within the still rather densely cytoplasmic cells) to the smallest bundles that arise in highly vacuolated parenchyma. The cross connections are parts of the primary vascular systems of the wholly primary plant bodies of corn and sugar cane.

#### SUMMARY

The procambial strands of *Zea mays* are initiated through longitudinal divisions in localized areas of the differentiating organs. The procambium of the largest strands is formed first in the still comparatively dense cytoplasmic parts of the shoot. The smaller bundles arise later in the more highly vacuolated part. A series of transitions occur

between the largest and the smallest bundles with regard to relative time of appearance in the differentiating organs and also with regard to the degree of vacuolation of the parenchyma from which the procambium arises.

More cells subdivide in the formation of the larger strand than in the development of the smaller ones. In its origin the procambium is not sharply separated from the adjacent parenchyma: when cells divide to produce procambium, part of a cell may become added to the procambium, while the other part may remain outside.

After the procambial strand is delimited, it increases in thickness by divisions within it. Radial growth dominates over the tangential; that is, tangential divisions predominate. As the bundle advances in its development, this orientation of the planes of division becomes increasingly evident. Despite the cambiumlike appearance of the vascular meristem, it is here interpreted as procambium, and all the vascular bundles in the whole plant are considered to be primary.

The first protophloem sieve tubes mature before the first protoxylem vessels. The protophloem is composed of sieve tubes only. In this it contrasts with the metaphloem, in which companion cells are associated with the sieve tubes. The protophloem is gradually crushed while the metaphloem matures. In like manner the conducting elements of the protoxylem are gradually destroyed while the metaxylem matures.

The bundle sheath differentiates partly from the outermost layer of the procambium strand, partly by addition of cells from the adjacent parenchyma, which undergo longitudinal divisions. Thus the bundle sheath is a part of the vascular bundle, but is not sharply separated from the tissue outside the bundle. The bundle sheath may be confluent with the hypodermal sclerenchyma, which arises partly like the peripheral sheath cells, by divisions and elongation of parenchyma cells, partly from the derivatives of the protoderm.

The protophloem and protoxylem are the conducting tissues of the elongating part of the shoot. The maturation of the metaphloem and metaxylem is delayed until the organs complete their elongation.

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## PLATES



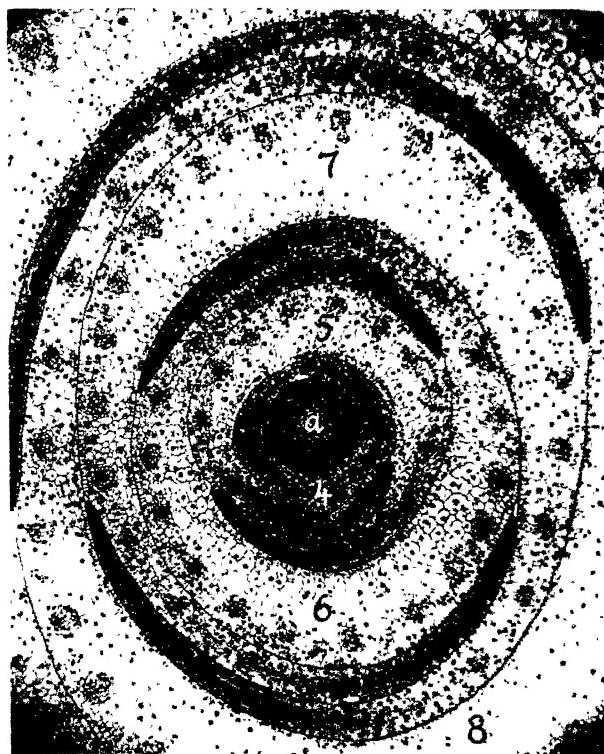


Plate 1.—Transverse section through the apex of a shoot, showing the stem apex (*a*) and the leaves enclosing the stem. The youngest leaf visible in this section was the fourth from the apex. Therefore the leaves in this figure are numbered 4 to 8. The three younger leaves occurred in sections cut at lower levels of the shoot ( $\times 77$ ).

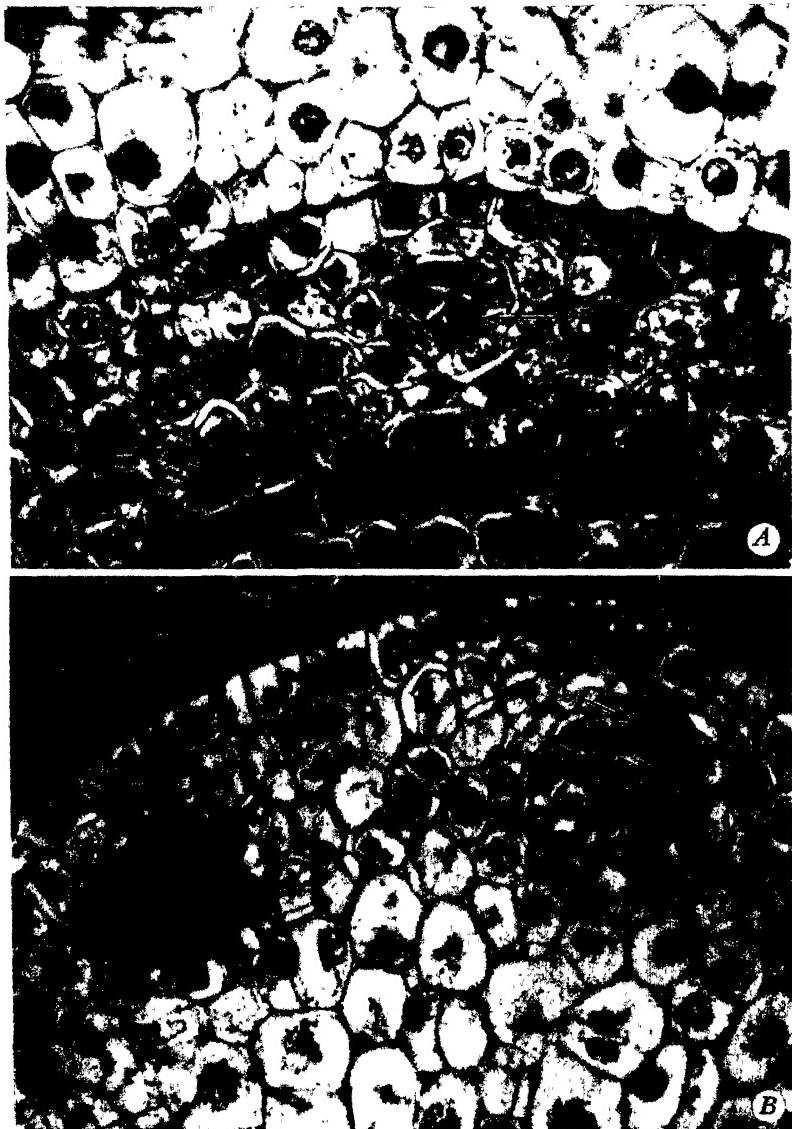


Plate 2.—Transverse sections of parts of leaves, showing early stages in the differentiation of the procambium. In A appears the very young median procambial strand (*mr*) of the second leaf below the apex. B shows the median (right) and the adjacent lateral (left) bundles of the fifth leaf below the apex (leaf 5 in plate 1). The median bundle has an immature sieve tube (*st*). (Both  $\times 750$ .)

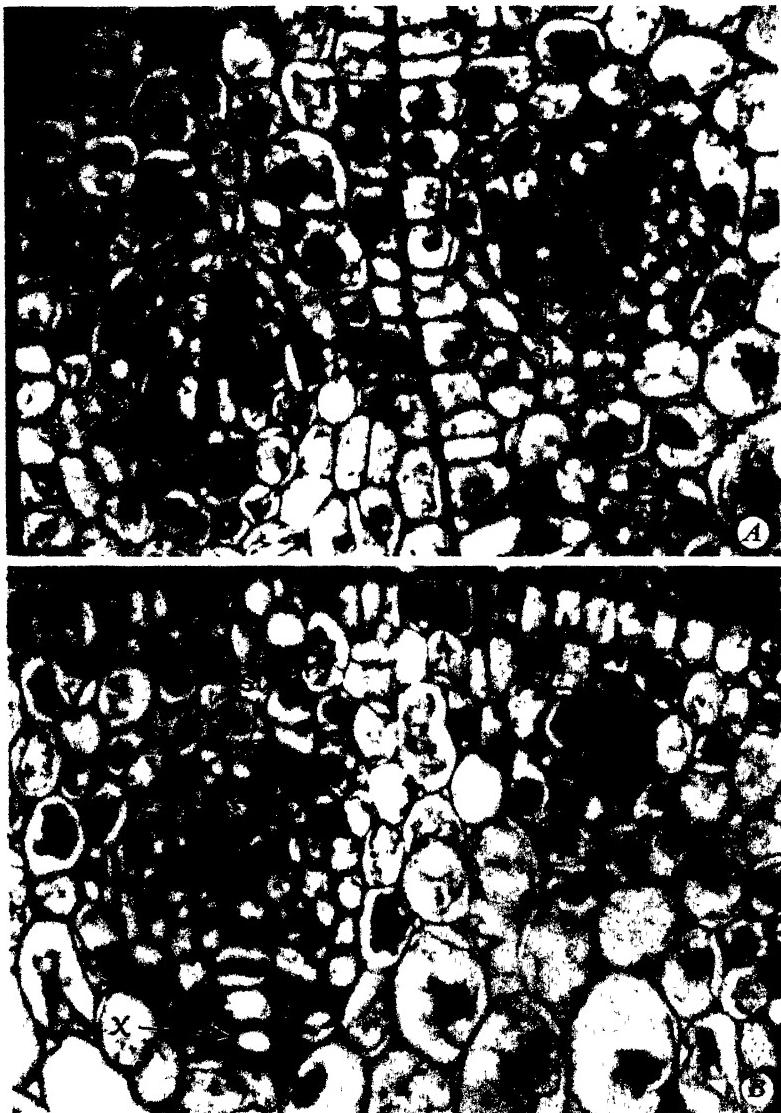


Plate 3.—Transverse sections of parts of leaves, showing early stages of vascular differentiation in the procambial bundles. In A is illustrated two first-rank lateral bundles, one (right) from the seventh, the other (left) from the eighth leaves below the apex. In each bundle the first sieve tube (*st*) is mature. In the bundle to the left the second sieve tube is almost mature. At B is shown, to the left, the median strand of leaf 7 with three mature sieve tubes (*st*) and one mature xylem element (*x*). A small procambial strand of second rank (bundle II in fig. 1, D) appears to the right in B. (Both  $\times 750$ .)

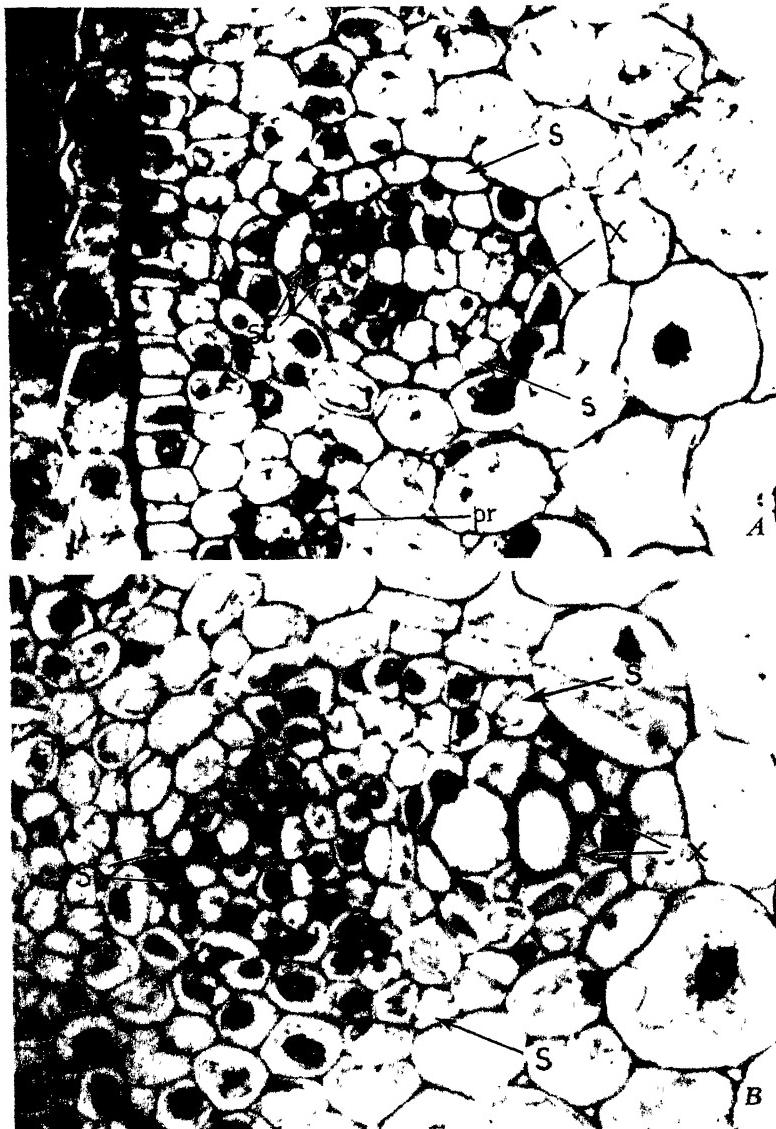


Plate 4.—Transverse sections of bundles from the sixth (A) and eighth (B) leaves below the apex. These were bundles of the first rank (bundles I in figure 1, D) located next to the median strands. The bundle in A shows two sieve tubes and two xylem elements. The smaller of the two xylem elements in B has been stretched somewhat, and the ringlike secondary wall thickening appears slightly tilted. Details are: pr, procambium; s, sheath; st, sieve tube; x, xylem element. (Both  $\times 750$ )

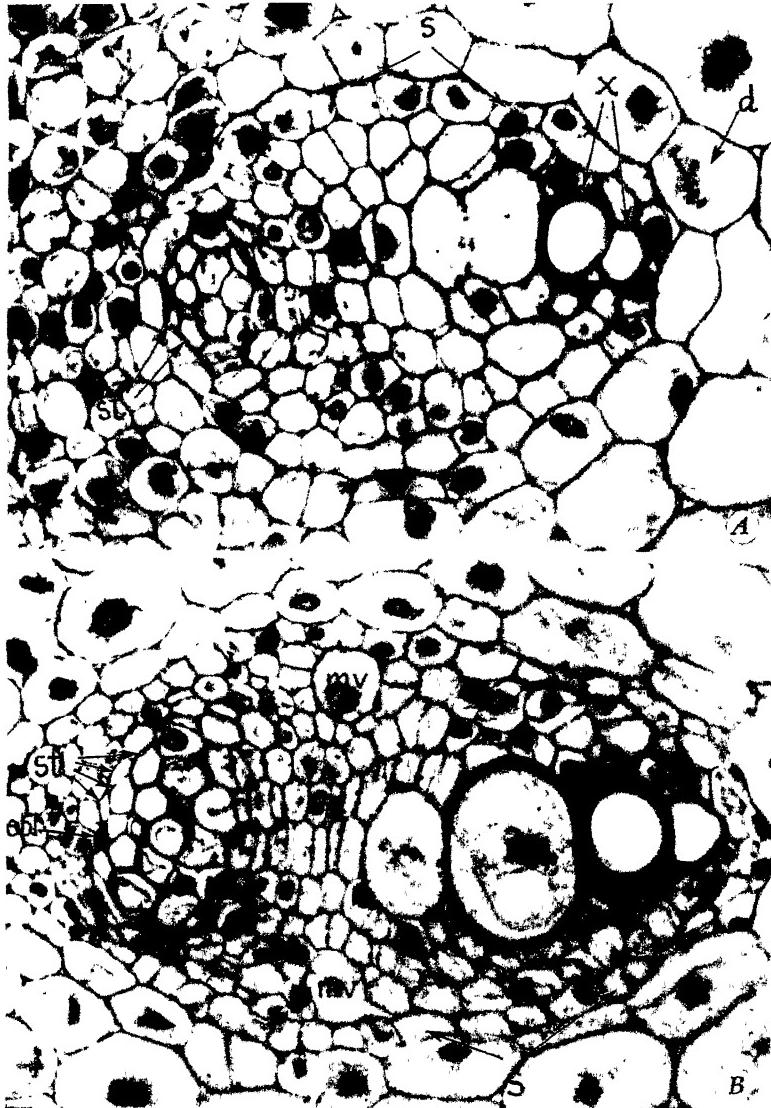


Plate 5.—Transverse sections of bundles showing an earlier (A) and later (B) stages in the differentiation of the protophloem and protoxylem. The bundle in A occurred in the tenth, the bundle in B in the thirteenth leaves below the apex. Both were lateral bundles of the first rank. Details are: d, dividing cell; mv, lateral metaxylem vessels; s, bundle sheath; st, sieve tube; x, xylem element. (A,  $\times 750$ , B,  $\times 480$ .)



Plate 6.—Longitudinal sections of a younger (*A*) and an older (*B*) vascular bundle. The bundle in *A* was somewhat older than the bundle in plate 5, *A*, the bundle in *B* was comparable with the one in plate 9, *A*. Details are: *c*, companion cell; *ep*, epidermis (the two adjacent layers of epidermis belong to two different leaves); *mv*, metaxylem vessel element; *s*, sheath; *sp*, sieve plate; *st*, sieve tube; *v*, vessel or vessel element. (*A*,  $\times 400$ ; *B*,  $\times 290$ )

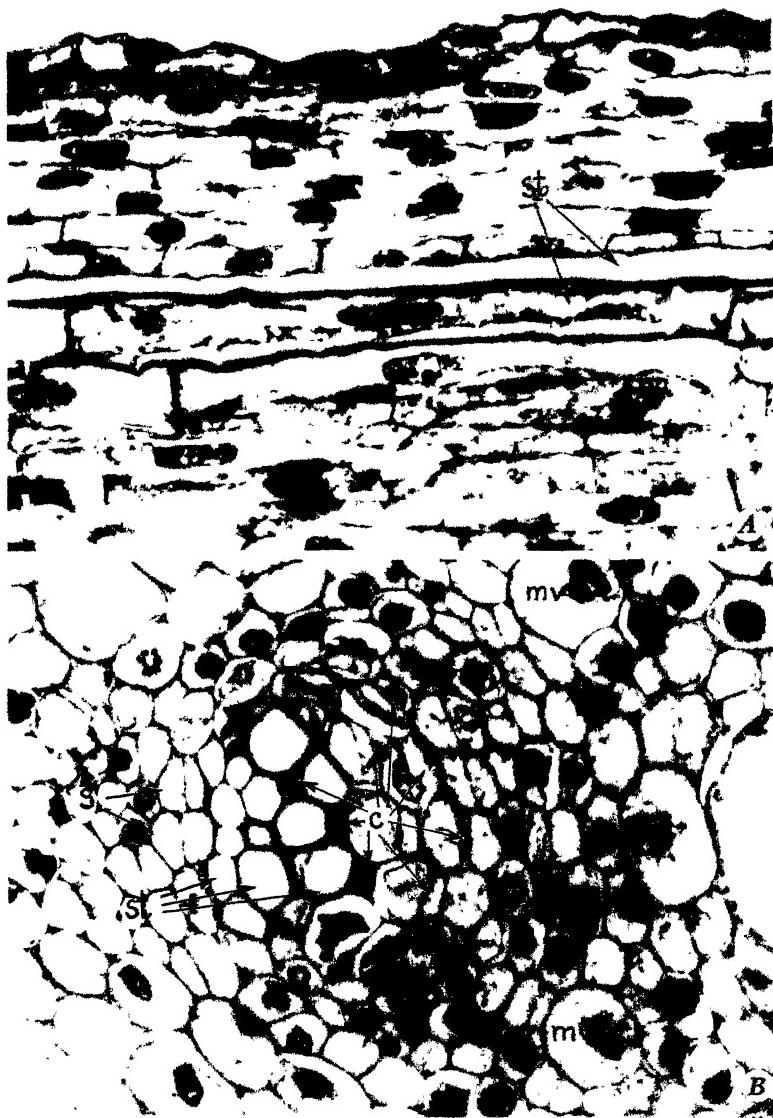


Plate 7.—A, Longitudinal section of a vascular bundle, showing a differentiating metaphloem sieve-tube element (lower cell labeled *st*) with pitted nacreous walls and a portion of an old and much elongated protophloem sieve tube (upper cell labeled *st*). B, Transverse section of part of a bundle showing mature protophloem (thin-walled cells apparently without contents to the left in the bundle). The first sieve tubes of the metaphloem with nacreous walls and companion cells occur to the right of the protophloem. The sheath cells (*s*) outside the protophloem have divided by periclinal walls. Details are: *c*, companion cell; *mv*, metaxylem vessel; *s*, sheath; *st*, sieve tube. (Both  $\times 750$ .)



Plate 8.—Transverse sections of parts of bundles showing two stages in phloem differentiation. In A is illustrated the beginning of protophloem crushing at *obl* and an early stage in metaphloem development. At B is depicted the stage of active metaphloem differentiation. Details are: *mv*, metaxylem vessel; *n*, nucleus, *obl*, obliterated protophloem (Both  $\times 750$ ).

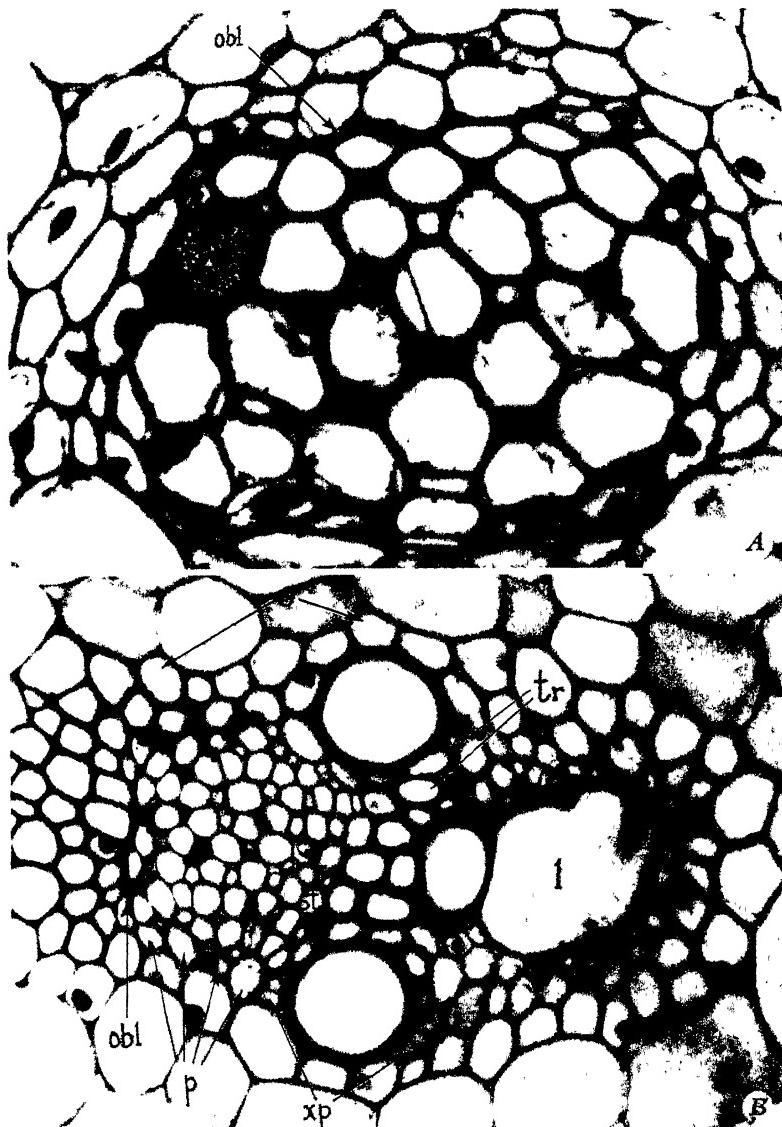


Plate 9.—*A*, Transverse section of almost mature metaphloem from a bundle in an internode. The protophloem is obliterated (*obl*). The first metaphloem sieve tubes are somewhat smaller than the later. A sieve plate is visible in one of the sieve tubes to the left. *B*, A mature vascular bundle from leaf 15 in transverse section. Details are *l*, lacuna of the protoxylem; *obl*, obliterated protophloem; *p*, parenchyma; *s*, sheath; *st*, sieve tube; *tr*, tracheary element; *xp*, xylem parenchyma. (*A*,  $\times 750$ ; *B*,  $\times 480$ )



Plate 10.—Longitudinal section through two nodes (*n*) and an internode (*in*). The leaf bases (*lb*) attached to these nodes are approximately the sixteenth and seventeenth from the apex. A part of an axillary bud appears at *ab*. The figure illustrates the continuity of the vascular bundles from node to node across the elongating internode. ( $\times 20$ .)

# H I L G A R D I A

*A Journal of Agricultural Science Published by  
the California Agricultural Experiment Station*

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VOL. 15

OCTOBER, 1943

No. 4

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## SOME NATURAL FACTORS LIMITING THE ABUNDANCE OF THE ALFALFA BUTTERFLY<sup>1</sup>

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### INTRODUCTION

THE EARLY HISTORY of the alfalfa butterfly as a pest is well covered in the works of Wildermuth (1911, 1914, 1920).<sup>4</sup> In California and other parts of the West the caterpillar of this butterfly, *Colias eurytheme* Boisduval,<sup>5</sup> is the most serious pest attacking alfalfa. Here, in cases of severe outbreaks, entire fields are often defoliated.

During the course of the alfalfa weevil investigation in the region adjacent to the San Francisco Bay and in the northwest portion of the San Joaquin Valley, it was observed that the amount of damage done by the alfalfa butterfly varied not only from year to year but from field to field. One of the reasons for this behavior came to light during September, 1938. In an alfalfa field near Tracy a large number of larvae were collected for use in toxicity studies. The alfalfa was about one third grown and supported a very large population of small larvae. At first it appeared that the developing population was sufficient to inflict serious damage. However, most of the larvae collected proved to be parasitized by a hymenopterous parasite, *Apanteles flaviconchae* Riley. Wildermuth (1914) probably referred to this parasite when he recorded *A. flavicombe* as a relatively unimportant parasite of the alfalfa butterfly at Salt Lake City, Utah. So effective was this parasite that on the next visit to the field the alfalfa butterfly larval population was greatly reduced, and the golden-colored cocoons of the parasite could be seen in large numbers attached to the

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<sup>4</sup> See "Literature Cited" for complete citations which are referred to in the text by author and date of publication.

<sup>5</sup> *Colias eurytheme* is used here because it is the name by which the alfalfa butterfly is known in this country. Clark (1941), however, has changed the name to *Colias chrysototheme* (Esper). He stated that a comparison between *eurytheme* and the European and Asiatic *chrysototheme* showed no features by which the two may be differentiated. He listed the forms as follows:

*Colias chrysototheme* (Esper)

*Colias chrysototheme eurytheme* Boisduval

*Colias chrysototheme eriphyle* W. H. Edwards

*Colias chrysototheme kootenai* Cockle

*Colias chrysototheme philodice* Godart

*Colias chrysototheme guatemalana* Staudinger

leaves of the alfalfa. The crop of alfalfa matured without any noticeable injury being inflicted by the alfalfa butterfly.

Because of the spectacular nature of this control, it was thought advisable to investigate carefully the part *Apanteles* played in restricting the damage done by the host insect. For the past four years in a restricted area, the seasonal trends of the alfalfa butterfly population and parasitism by *Apanteles* have been followed, and are reported in this paper. In the course of this study numerous other insect parasites of the alfalfa butterfly were encountered. It is possible that several of these might serve as important natural checks, although preliminary observations indicate that none of these approached *Apanteles* in importance. It is hoped that it will be possible, in the future, to study them more thoroughly. Such an investigation would be very desirable to complete the picture. The main purpose of this paper is to discuss the natural enemies of the alfalfa butterfly which markedly affect the populations of this insect and which should be carefully considered in planning any control measures. A wilt disease which attacks the alfalfa butterfly is also discussed because of a relationship that appears to exist between this disease, the parasite (*Apanteles flaviconchae* Riley), and the alfalfa butterfly.

The area covered in this study embraces a region adjacent to the San Francisco Bay, and the west side of the lower San Joaquin Valley which includes the towns of Tracy, Vernalis, Westley, and Patterson. A striking difference was noted in alfalfa butterfly populations within these areas, which raises a question as to how far the findings of this study can be applied to other regions. Certainly caution should be used in comparing areas having markedly different climates.

However, a survey in 1942 of many of the alfalfa-producing sections in California revealed the parasite *Apanteles flaviconchae* to be present in all the areas visited. The parasite has been collected in the following counties: Alameda, Butte, Contra Costa, Fresno, Imperial, Kern, Kings, Los Angeles, Madera, Merced, Napa, Orange, Riverside, San Bernardino, San Diego, San Joaquin, Solano, Stanislaus, Tulare, Ventura, Yolo, and Yuba. In most of these the wilt disease has also been observed. It is the belief of the authors that these two important factors in the ecology of the alfalfa butterfly operate in the same manner as described in this paper throughout California.

#### EXPERIMENTAL METHODS USED

Populations of alfalfa butterfly larvae were determined by sweeping<sup>6</sup> alfalfa fields in the areas studied. Usually at least 100 sweeps were made in each field, although fewer sweeps were sometimes made where extremely large populations were encountered. During the periods when the insect was most active, surveys were made at intervals of from 7 to 14 days, and the number of fields examined in the San Joaquin usually ranged between 10 and 15. In the region adjacent to San Francisco Bay the number of fields ranged from 4 to 8. Fields were seldom swept before the plants were one fourth grown, and an effort was made to select those fields representative of average conditions. The larvae

<sup>6</sup> A No. 5 "Harrimac" collapsing, steel frame, landing net, manufactured by the Richardson Rod and Reel Company, Chicago, was used throughout this investigation. The frame is an ellipse, the major axis of which is 15 inches and the minor axis, 13 inches.

collected were segregated into two groups according to size. The "large" group contained all caterpillars which had advanced beyond the earliest part of the fourth instar, while all other larvae were considered "small."

The amount of parasitism by *Apanteles* was determined in the field. This was done by holding a larva between the thumb and forefinger. The head of the larva was pulled off with a forceps and enough pressure exerted on the larva to cause the parasite, if present, to be expelled. If the larva of the parasite is large, it spurts out; if small, it comes out usually adhering to the intestinal tract where it is easily seen. With a little practice, the examination can be made rapidly and accurately. It was not necessary to treat all larvae in the manner described above for, as the parasite develops, it distends the posterior end of the host (fig. 1) and can thus be detected. While *Apanteles* parasitizes the first three larval instars of the alfalfa butterfly, the first instar larvae were never examined because of their very small size.

In determining the number of small larvae parasitized, very late second, third, and early fourth instars were selected. These ranged from about 5 to 11 millimeters in length and were easiest to handle. The percentage of small larvae given as being parasitized was based on the number found to be parasitized in this size range. This method of determination was believed to give a very conservative estimate of the small larvae that were parasitized. At the size range indicated the parasites had developed to a size where they could more readily be seen. It is possible that *Apanteles* may parasitize larvae of a size above the range indicated, but this seems to be rare. If oviposition had occurred recently in a larva, the egg or very young parasite would likely be overlooked. However, since commonly 95 to 100 per cent of the larvae were found parasitized in counts made at progressive intervals, it would indicate that in most cases very few parasites are missed by the method of examination described above.

If the population in a field permitted, 100 larvae were examined for parasitism. In constructing graphs showing the percentage of parasitism, the figures used are based on the total number of parasitized and nonparasitized larvae of the size-range, as previously described, examined on any particular date.

The rearing dishes used for life-history studies were of the same type as used in the rearing of the garden centipede (Michelbacher, 1938). They were made by thoroughly mixing 10 parts of plaster of paris, 3 parts finely ground soil, and 1 part of animal charcoal. Water was added to the mixture and the whole stirred until the material had the consistency of rather thick cream. This was then poured into stender dishes to about the depth of  $\frac{1}{4}$  inch and allowed to set. These stender dishes, with their absorbent plaster, were found to be very well suited for rearing individual larvae and made accurate obser-vations possible. The outside dimensions of the dishes used were: height, 30 millimeters and diameter, 50 millimeters. Fresh food was given to the caterpillars once a day during the first four instars, and twice a day during the fifth

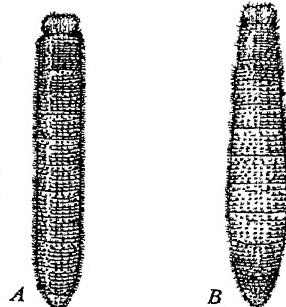


Fig. 1.—A, Normal alfalfa butterfly larva in early instar stage. B, Parasitized larva, showing swollen posterior end. (Both  $\times 5$ .)

instar. After pupation occurred the individuals were placed in pint Mason jars. To avoid spreading disease from one culture to another certain aseptic precautions were followed. Instruments were dipped in 10 per cent carbolic acid solution for at least 30 seconds, and the dishes were cleaned of feces with a camel's hair brush.

The temperature cabinets used in the investigation did not fluctuate more than  $\pm 1^{\circ}$  F. The eggs used for life-history studies were obtained from butterflies brought in from the field, and the parasites used were reared from parasitized alfalfa butterfly larvae collected in the field.

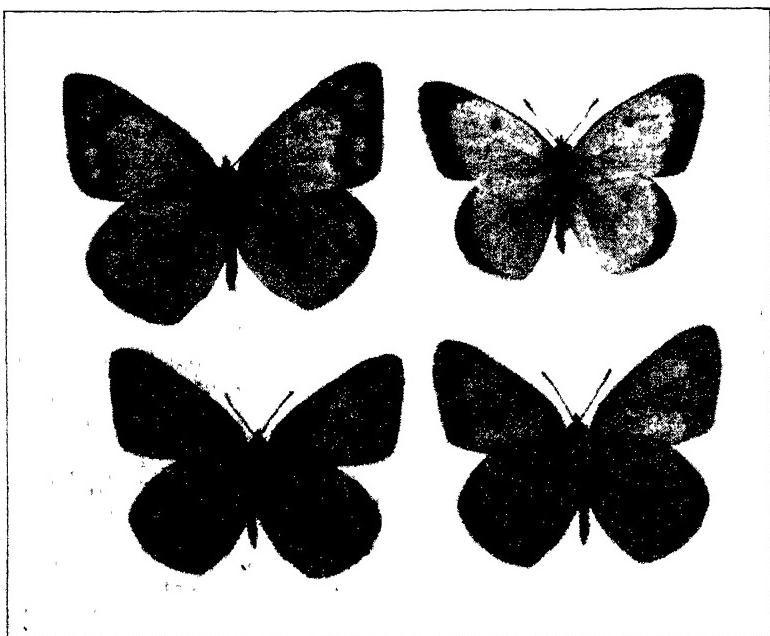


Fig. 2.—Adults of the alfalfa butterfly. Left, females; right, males; upper row, dorsal view; lower row, ventral view. (Natural size.)

#### LIFE HISTORY AND DEVELOPMENT OF THE ALFALFA BUTTERFLY

Everyone who has observed the alfalfa butterfly (fig. 2) in the field is struck by the rapidity of its development during the summer months. During this time, the broods appear about a month apart. The eggs (fig. 3), which are laid singly on the leaves of the alfalfa plants, are ribbed, and somewhat cigar-shaped. When first laid they are pearly white but as incubation continues they turn pinkish and, before hatching, the black head of the larva, which is apical in position, shows through the delicate eggshells. The hatching larva chews its way out, and frequently eats the whole shell before starting to feed on the leaves. The black head of the first instar larva distinguishes it from all other

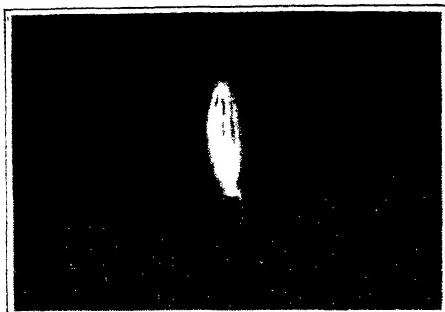


Fig. 3.—Egg of the alfalfa butterfly. ( $\times 15.$ )



Fig. 4.—Mature larvae of the alfalfa butterfly as seen on alfalfa plants. (About natural size.)

stages. Before reaching maturity the larva casts its skin four times. The full-grown larva (fig. 4) is about 30 millimeters, or about  $1\frac{1}{4}$  inches in length. It is of velvet-green color and along either side there is a white line with red markings. Down the back there may be two fine white lines (fig. 5, A). The length of the larvae in the different instars is shown in table 1. At first the larvae grow slowly and their feeding is not noticeable. However, by the time the fourth instar is reached considerable food is consumed and during the final

instar the larvae have a voracious appetite. Upon reaching maturity the larvae transform into light-green pupae (fig. 5, *B*) which are attached to the stubble and stems of the alfalfa. As the butterfly develops it can be seen within the pupal case and soon after this, it emerges. Most of the butterflies are yellow

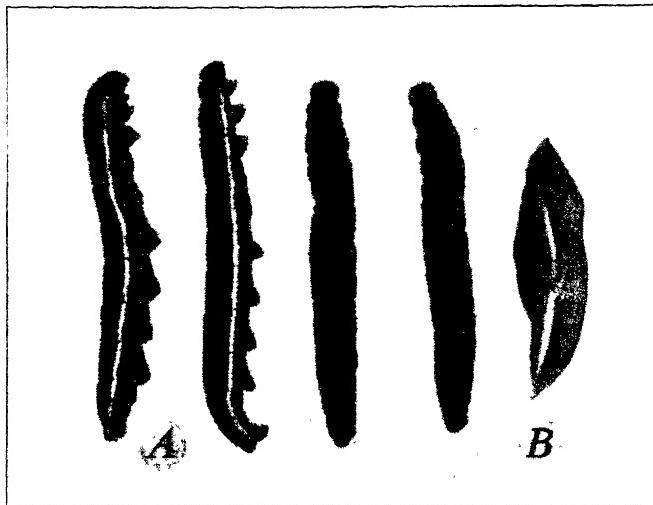


Fig. 5.—*A*, Four mature alfalfa butterfly larvae showing some differences in markings. *B*, Pupa. (All  $\times 1.5$ .)

TABLE 1  
LENGTH OF ALFALFA BUTTERFLY CATERPILLARS  
IN THE DIFFERENT INSTARS

Instar	Number examined	Length in millimeters	
		Range	Mean
Newly emerged...	50	1.8-1.8	1.80
First...	22	1.8-3.0	—*
Second...	21	3.0-5.5	4.05 $\pm$ 0.17
Third...	21	4.5-8.0	6.31 $\pm$ 0.23
Fourth...	9	8.0-15.0	8.94 $\pm$ 0.51
Fifth (early)...	11	15.0-23.0	19.00 $\pm$ 0.87
Fifth (late)...	13	26.0-29.0	27.69 $\pm$ 0.29

\* Data not available.

with black markings. The males can be distinguished from the females in that they have on the upper, outer surfaces of the wings a solid black border. The females are usually slightly larger and the black border is broken by yellow spots. The females also occur in a white color phase.

Some laboratory studies were conducted on the rate of development and duration of the various stages at constant temperatures of 80° and 90° F. The results of these studies are given in table 2. The time necessary for the butterfly to complete its life cycle from egg to adult at 80° F was approximately 21 days; and at 90°, about 17 days. The mean temperature in the portion of the

San Joaquin Valley where most of this investigation was conducted does not reach 80°, although over part of the area a mean temperature of close to 75° exists for a period of a month or two.

Although the present authors are aware that these data were obtained at constant temperatures and that the butterfly exists under highly fluctuating temperatures, they feel justified in stating that the alfalfa butterfly can easily complete its life cycle in a month during the summer; furthermore all the field observations indicate that during midsummer the life cycle is completed in 30 days or less. Although evidence in the literature is very scanty, it indicates that fluctuating temperatures may even accelerate development (Imms, 1937).

According to Wildermuth (1920) the alfalfa butterfly passes the winter in the pupal stage, although he stated that in the Southwest both larvae and

TABLE 2

## RATE OF DEVELOPMENT OF THE ALFALFA BUTTERFLY AT CONSTANT TEMPERATURES

Stage	Number of individuals	Days at 80° F		Number of individuals	Days at 90° F	
		Range	Mean		Range	Mean
Egg	20	3-3	3 ± 0.01	24	2-3	2.5
First instar	38	2-3	2.6 ± 0.08	33	0.5-3	2.1 ± 0.12
Second instar	33	1-3	2.2 ± 0.06	41	1-3	1.8 ± 0.10
Third instar	25	1-3	1.8 ± 0.13	31	1-3	1.7 ± 0.11
Fourth instar	14	2-3	2.3 ± 0.12	22	1-3	2.1 ± 0.09
Fifth instar	6	4-5	4.3 ± 0.21	10	2-4	2.9 ± 0.18
Pupa	5	5-5	5 ± 0.01	8	4-5	4.1 ± 0.13
Total (hatch to emergence)	..	...	18.2	..	...	14.7
Total (time egg laid to emergence)	.....	..	21.2	..	...	17.2

adults could be taken every month in the winter. In the present investigation no thorough study has been made to determine how the insect passes the winter. In mild winters larvae can be collected during any month. They have not been collected in abundance, but when a search was made a few at least could be found. Adult butterflies are not seen to any extent until about the first of April. In cold winters, particularly, the insect probably passes the coldest period in the pupal stage, although it is possible that the adult may pass the winter in well-protected secluded places. Under any conditions, the winter and spring activity of the alfalfa butterfly is not great, and it is never found in abundance at that time. Shortly after the first of June, however, there is a rise in the larval population. Although not very noticeable it probably marks the first summer brood. There is a second much larger brood in July, and a still larger one during the end of August and the first part of September. Following this very large brood, there is a smaller one. The first severe attack by the pest occurs on the fourth and fifth crops. The seasonal trend of the larval population in the San Joaquin Valley for 1939-1942 inclusive are shown in figures 6 to 9. In the summer and fall there are four more or less distinct broods.

The seasonal trend of the larval population in the agricultural region adjacent to San Francisco Bay is very different from that in the northwest portion

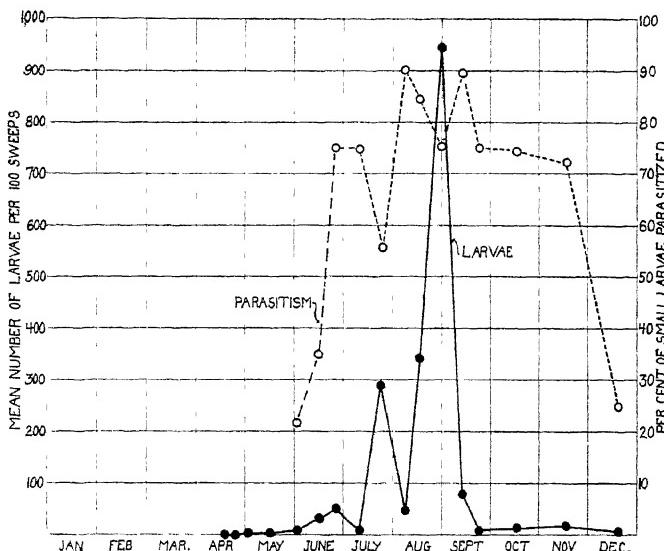


Fig. 6.—Alfalfa butterfly larval population and the per cent of the small larvae parasitized by *Apanteles flaviconchae*, in the northwest portion of the San Joaquin Valley, 1939. The part of the parasitism curve representing June is shown by dot and dash, since the percentage of parasitism was only estimated.

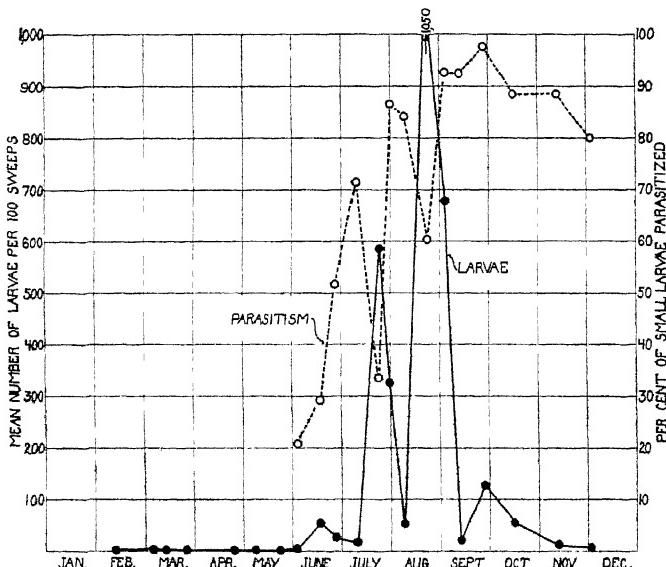


Fig. 7.—Alfalfa butterfly larval population and the per cent of small larvae parasitized by *Apanteles flaviconchae*, in the northwest portion of the San Joaquin Valley, 1940.

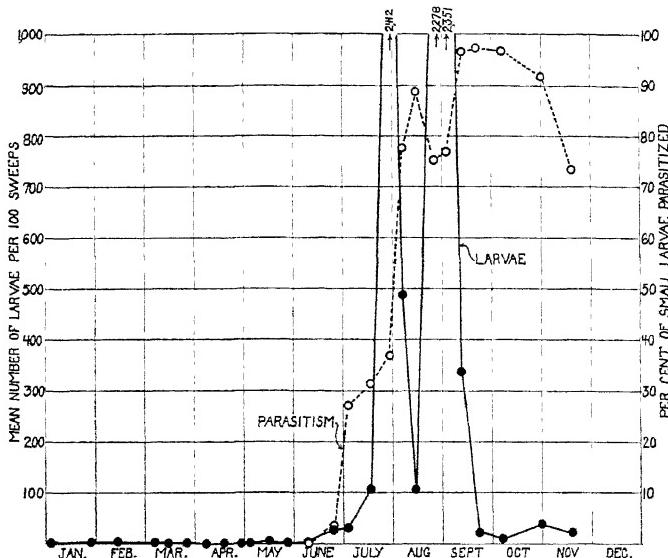


Fig. 8.—Alfalfa butterfly larval population and the per cent of small larvae parasitized by *Apanteles flaviconchae*, in the northwest portion of the San Joaquin Valley, 1941.

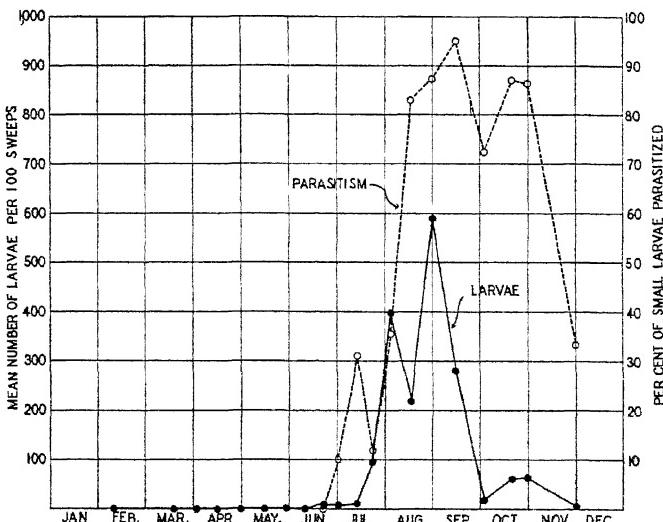


Fig. 9.—Alfalfa butterfly larval population and the per cent of small larvae parasitized by *Apanteles flaviconchae*, in the northwest portion of the San Joaquin Valley, 1942.

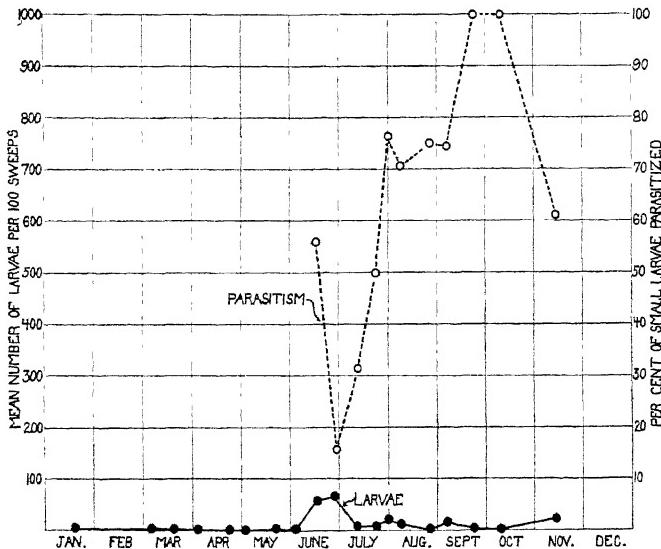


Fig. 10.—Alfalfa butterfly larval population and per cent of small larvae parasitized by *Apanteles flaviconchae*, in the agricultural region adjacent to San Francisco Bay, 1940.

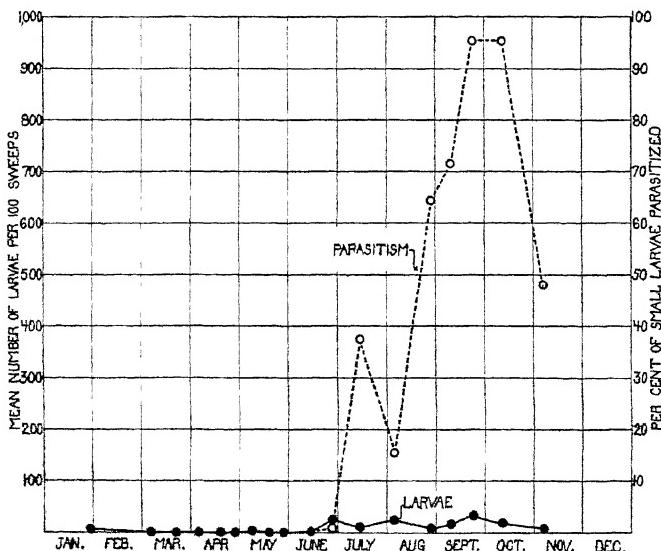


Fig. 11.—Alfalfa butterfly larval population and per cent of the small larvae parasitized by *Apanteles flaviconchae*, in the agricultural region adjacent to San Francisco Bay, 1941.

of the San Joaquin Valley. The winter activity is much the same but a wide departure occurs in summer activity. There is no marked build-up such as occurs in the San Joaquin Valley. Some factor, possibly associated with climate, is effective in limiting the numbers of alfalfa butterflies in the more coastal areas. The seasonal trends for 1940 and 1941 are shown in figures 10 and 11.

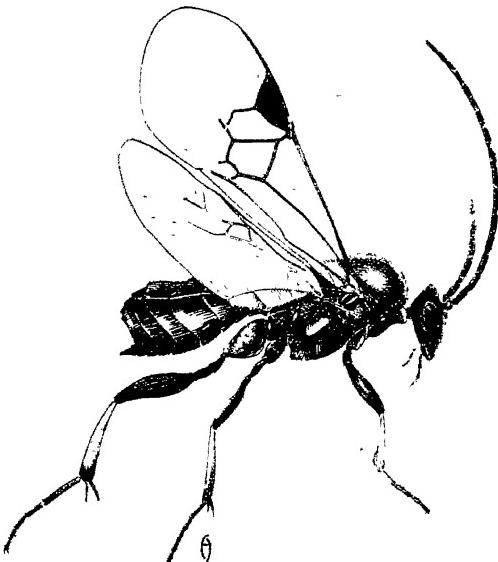


Fig. 12.—Adult *Apanteles flaviconchae*. ( $\times 17$ .)

#### LIFE HISTORY AND DEVELOPMENT OF *APANTELES FLAVICONCHAE*

*Apanteles flaviconchae* (fig. 12) is a hymenopterous parasite of the alfalfa butterfly larva. It completes its development (fig. 13) in a relatively short period and issues from the host larvae long before they have completed their growth. Soon after emerging, it spins a golden-colored or yellowish silken cocoon from which the adult emerges.

These cocoons are not gregarious as has been reported by Muesebeck (1921) and Viereck (1916), but are usually spun singly on the upper surface of an alfalfa leaf. One would suspect that the apparent gregariousness reported earlier was due probably to an unnatural method of rearing.

The time necessary for *Apanteles* to complete its development at a constant temperature of 80° F. was investigated. The information obtained is summarized in table 3. The time to complete the life cycle ranged from 11 to 13 days and depended upon the stage of the host parasitized. This study has shown that *Apanteles* is able to complete its life cycle in much less time than the alfalfa butterfly, and since it also is apparently able to find its host with ease, it has a combination of characters which make it a formidable factor in checking the damage done by the alfalfa butterfly.

*Effect of Apanteles upon the Host.*—Apparently only the early instars of the alfalfa butterfly are attacked by *Apanteles*. No difficulty was encountered in parasitizing the larvae in the laboratory. The parasites oviposit freely in any of the first three instars. In the field it is possible that the first- and second-instar larvae are more heavily parasitized. A host larva casts its skin twice after being parasitized in the first or second instar; and only once if it is parasitized in the third instar. Further development of the host is arrested, and the parasite completes its development and emerges. Thus the instar stage from which the parasite emerges is prolonged. It was noted that *Apanteles* emerged from host larvae of the third and fourth instars. That is certainly the usual

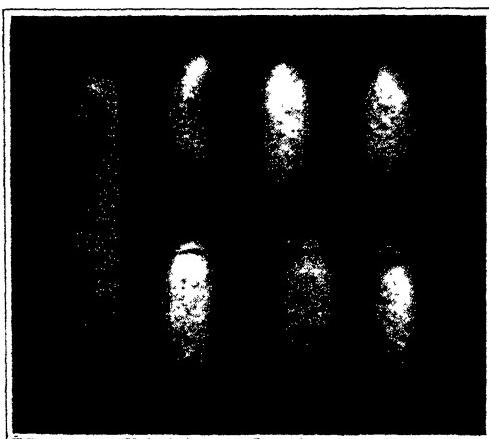


Fig. 13.—Stages in the development of *Apanteles flaviconiae*. Left, host caterpillar from which the parasite is about ready to emerge. The upper row shows at the left a mature parasite larva, and at the right two cocoons of the parasite. The lower row shows three cocoons from which the parasite has emerged. ( $\times 5$ .)

condition, although Floyd (1940) reported rearing the parasite from fifth-instar larvae and made no mention of rearing it from any of the earlier instars.

The length of time necessary for the parasite to complete its life history is increased if oviposition occurs in larvae of the first instar; this is probably because of the very small size of the host larva at the time of oviposition. Apparently the available food is so limited that more time is needed than when later instars are parasitized. The hosts were killed outright when the parasites emerged from larvae that were parasitized in the first or second instar. Where third-instar larvae were parasitized the hosts were thoroughly incapacitated but in some cases they remained alive for several days following the emergence of the parasite. *Apanteles* destroys its host before it has had opportunity to do much feeding; and, furthermore, it may parasitize nearly the whole larval population. These facts make *Apanteles* a very effective natural check on the alfalfa butterfly.

*Apanteles* will lay more than a single egg in a host larva. In the laboratory some evidence was obtained to indicate that a host might be killed by having

too many eggs deposited in it. It is very possible that this happens in the fields where the adult parasite population is large and the host population is small. Such behavior is not to the best advantage of the parasite, and may reduce its effectiveness.

Because *Apanteles* is a parasite of the alfalfa butterfly, its seasonal population trend is closely associated with that of its host. *Apanteles* has been taken every month of the year except January. In 1940 it was not taken until March 13, but in 1941 it was found rather easily on February 13, and in 1942 parasitized alfalfa butterfly larvae were taken on February 10. The way in which it passes the coldest part of the year has not been investigated but it probably survives the winter in the adult stage or in the cocoon. As in the case of its host, *Apanteles* does not exhibit a great deal of activity before the first of June. From this time on, the parasite becomes more abundant. The number of host

TABLE 3  
TIME REQUIRED FOR THE DEVELOPMENT OF *Apanteles* AT 80° F

Stage of host parasitized	Stage of host from which parasite emerged	Days in host	Days in cocoon stage	Total days from oviposition to emergence
First instar	Third instar	8½	4½	13
Second instar	Fourth instar	7	4	11
Third instar	Fourth instar	7	4	11

larvae parasitized varies considerably during the peak broods of the alfalfa butterfly, but at all times a large proportion of the smaller larvae are parasitized. Although there may be considerable variation in the degree of parasitism in early summer in different years, this difference is lost by late summer when nearly all the larvae are parasitized; and this high degree of parasitism continues into December.

The seasonal parasitism trends in the northwest portion of the San Joaquin Valley for the years 1939–1941, inclusive, are shown in figures 6 to 9, and for the region adjacent to the San Francisco Bay for the years 1940 and 1941, in figures 10 and 11. The trends are plotted only for the months of June through November. Although a number of parasitized larvae may be taken during the winter and spring, not a sufficient number could be collected on any particular survey to give a dependable figure. Even during the summer in the region adjacent to the San Francisco Bay, some of the percentages plotted were based on an examination of relatively few larvae.

#### EFFECTIVENESS OF PARASITISM BY APANTELES

The value of *Apanteles* in controlling the alfalfa butterfly can hardly be overestimated. It is one of the most important natural factors holding this serious pest in check. In certain fields and districts it has completely dominated the situation, and time and again it has saved the alfalfa crop from nearly complete destruction. The effectiveness of the parasite has not been so complete in some years as others. In 1939 not a single seriously infested alfalfa field was observed in a region that covered an area from west of Tracy to south of Vernalis. In this large area the greatest number of alfalfa butterfly larvae

collected per 100 sweeps never exceeded 220. Over most of this area the degree of parasitism of small larvae in any field during the summer seldom fell below 80 per cent. The completeness of parasitism is corroborated by the fact that very few large larvae were collected at any time in this region. The only heavy infestation of the alfalfa butterfly encountered in the northwest portion of the San Joaquin Valley in 1939 was in a small region near Westley. Here several fields were seriously damaged, although in the most heavily infested area there were some fields that were fully protected by *Apanteles*. For example, there was one field where 685 larvae were collected per 100 sweeps, all of them small, and 99 per cent were parasitized.

In 1940 the outbreak of the butterfly was more severe than in 1939. Scattered through most of the area there were fields that suffered serious injury. Even in the face of this attack *Apanteles* played a very important role in reducing damage and many fields were completely protected.

The 1941 butterfly outbreak was the most serious observed since work on the investigation of alfalfa insects was started in 1933. In scattered fields the alfalfa was almost defoliated, and in others it was seriously attacked; nevertheless, *Apanteles* saved many fields from economic loss.

It is probable that the damage done by the alfalfa butterfly during the past four years represents the greatest fluctuation that might be expected to occur. The immediate question that arises is: why should there be such a wide range in the damage done from year to year? It may be that climate is partly responsible. Parasitism may also play a part, and in looking over the experimental data there is some evidence that strongly indicates that this is the case. If the amount of parasitism during June, in 1939, 1940, and 1941 is examined, it is noted as greatest in 1939, somewhat less in 1940, and considerably less in 1941. The trends for these three years are shown in figures 6 to 8 for the months of June through November. The figures plotted are the percentage of larvae parasitized, based upon the total number examined for parasites in all fields surveyed on any particular date. Information for June 1939 is indicated by dot-and-dash line, and represents an estimate, only because the data taken up to that time were general and not based on actual counts. It should be noted that the conditions which exist in individual fields or even districts, are lost when information is presented in the graphical form just mentioned. Fields having a high population exert more influence on a graph because of the larger number of larvae that are available for examination; in many fields only a few larvae could be collected and parasitism in such areas might be extremely high, but because of the small number of larvae available the importance of parasitism is not fully shown.

The early parasitism trend during the time that the first brood of alfalfa butterfly larvae is making its appearance may give some indication of the destructiveness of the later broods. In general, the greater the degree of parasitism in June, the less serious will be the attacks from the later broods. This is certainly indicated in figures 6, 7 and 8. The first brood is small and if parasitism is high at that time, it is possible that enough larvae will be destroyed so that the later broods will be much reduced. Further, a large population of adult parasites is produced early and these might play an important part in holding the larval butterfly population in check. During the early summer,

when the environmental resistance is apparently low, aside from cultural kill at the time of cutting, *Apanteles* appears to be the principal factor in the environmental resistance effective in reducing size of the brood. The wilt disease that becomes so important later in the summer apparently plays no part at this time. For this reason, if *Apanteles* is slow in starting, the amount of parasitism will be small during this critical period, and the stage is set for later serious infestations of the alfalfa butterfly.

Further evidence in support of this is shown in table 4 in which some relations existing between the alfalfa butterfly and *Apanteles* during the development of the first brood for the years 1939 to 1942, inclusive, are summarized. With the exception of 1942, the higher the degree of parasitism of small larvae the greater the proportion of parasites to each large caterpillar. This is important because it is the large caterpillars that have escaped parasitism, that give rise to the later broods of butterflies. Thus the more parasites per

TABLE 4  
PARASITISM BY *Apanteles* IN THE FIRST BROOD OF THE ALFALFA BUTTERFLY LARVAE IN THE YEARS 1939-1942

Year	Average number of small larvae per field (100 sweeps)	Average number of parasitized larvae per field (100 sweeps)	Per cent of parasitized larvae	Average number of large larvae per field (100 sweeps)	Number of parasites per large larva
1939 ...	8.40	4.30	51.20	0.71	6.10
1940 . .	13.10	4.90	37.40	18.00	0.27
1941 . .	7.00	1.00	14.30	14.00	0.07
1942 ..	3.10	0.30	9.70	4.70	0.06

caterpillar the greater the environmental resistance will be on the following broods. In 1939 this relation was 6.1 parasites to each large larva while in 1941 it was 0.07 to each large larva. In the former year very little damage was done by the succeeding butterfly broods, while in the latter year severe damage occurred. In 1940 some damage occurred and, although much less than in 1941, it was considerably more than in 1939. The weather in the late spring and early summer of 1942 was cool. There was a marked departure from the normal, and the weather conditions were somewhat similar to those which normally occur nearer the coast, a climatic region where damage by the alfalfa butterfly has never been observed by the authors. The cooler weather conditions probably account for the small first brood. Despite the low parasitism, the ratio of parasites to large alfalfa caterpillars was 0.06 to 1.0, the lack of damage in 1942 can be attributed to the small first brood. It is only in such cases where parasitism is negligible that the size of the brood is important in determining the destructiveness of later populations.

The percentage of parasitism during the first brood and its relation to the size of the later broods is a very complicated matter. First, the amount of parasitism is affected by the size of the fall population of *Apanteles* and *Colias*, the winter mortality, and various climatic and other unknown factors during spring and early summer. Moreover, the effect of the parasite may be modified by cutting and other cultural practices, by the wilt disease, and the climate prevailing for the season. In spite of this we feel that the amount of parasitism in the first brood is indicative of later infestations, especially when taken in

consideration with the amount of large larvae in that brood. In the four years that we have studied these insects, in only one field where the parasitism of small larvae was over 35 per cent of the first brood did serious infestations develop later; and in that case the first brood produced an unusually high percentage of large worms.

The data on the first brood of alfalfa butterfly gives an excellent field illustration of the effect of host density on parasitism. Where host density is low, correspondingly small parasite populations occur; but where the population density of small larvae is high many parasites complete their development. This is indicated in the following tabulation:

Small larvae per 100 sweeps	Parasites produced
0	0.00
1	0.15
2	0.36
3	0.50
4-10	1.33
11-15	2.59
16-25	4.55
26-75	11.80
76+	32.90

These results probably can be explained by the difficulty the parasite has in finding its host when the population density is low.

If for some reason *Apanteles* is not able to check the later broods of the alfalfa butterfly effectively, the wilt disease will enter the picture. Therefore, the wilt disease becomes more evident when *Apanteles* is less effective. For this reason wilt disease played a more important role in 1941 than in the previous years. However, it appears to be present at all times and reduces larval populations which have escaped other natural enemies.

In order to show the part *Apanteles* played in limiting damage of the alfalfa butterfly, tables 5 to 7 are included. These tables give the alfalfa butterfly larval population trends and the percentage of parasitism of small larvae by *Apanteles* during the development of the midsummer infestation of the alfalfa butterfly in the northwest portion of the San Joaquin Valley for the years 1939, 1940, and 1941, in individual fields. In 1939 the larvae were not segregated into large and small larvae, and for that year only the total number of larvae collected is given. From these tables it is seen that in many cases *Apanteles* was very effective in reducing the alfalfa butterfly population. For instance, on September 3, 1940, in one field near Tracy, 2,180 larvae were collected per 100 sweeps. Of this number, 330 were large; and of the 1,850 small ones, 99 per cent were parasitized. On September 3, 1941, in one field near Westley, 2,884 larvae were collected per 100 sweeps. Of these, 720 were large, and 91 per cent of the 2,164 small ones were parasitized. This same condition also existed in all the surrounding fields. The populations would have been much greater if it had not been for *Apanteles*. Parasitized larvae are killed before they reach maturity; consequently many are removed as compared with a field where the effects of the parasite are absent.

In this study it has been observed that the number of butterfly adults noted is little indication of how much damage will be done by the pest. If the envi-

TABLE 5

ALFALFA BUTTERFLY LARVAL POPULATIONS AND PARASITISM BY *Apaneles* DURING THE  
MIDSUMMER INFESTATION IN THE NORTHWEST PORTION OF THE  
SAN JOAQUIN VALLEY, IN 1939

Location of field	Total larvae, per 100 sweeps	Per cent of small larvae parasitized
July 10		
Tracy	10	79
1 mile east of Tracy	8	38
4 miles south of Tracy	12	82
4 miles north of Vernalis	10	13
2 miles south of Westley	7	85
Patterson	2	100
Patterson	3	100
July 24		
5 miles north of Tracy	82	67
5 miles north of Tracy	158	27
1 mile east of Tracy	25	90
1 mile east of Tracy	50	94
6 miles south of Tracy	60	82
1 mile north of Westley	127	72
2 miles south of Westley	778	22
2 miles south of Westley	129	13
2 miles north of Patterson	65	91
August 7		
5 miles north of Tracy	10	
1 mile east of Tracy	10	
1 mile east of Tracy	30	80
5 miles south of Tracy	103	88
2 miles south of Westley	121	95
Patterson	10	92
August 16		
Tracy	2	..
1 mile east of Tracy	2	..
1 mile east of Tracy	2	..
6 miles south of Tracy	10	100
4 miles north of Vernalis	2	100
2 miles south of Westley	875	98
2 miles south of Westley	1,710	70

TABLE 5 (*Continued*)

Location of field	Total larvae, per 100 sweeps	Per cent of small larvae parasitized
August 31		
5 miles north of Tracy	175	53
5 miles north of Tracy	170	93
1 mile east of Tracy	171	94
6 miles south of Tracy	210	95
4 miles north of Vernalis	10	
2 miles south of Vernalis	160	87
2 miles north of Westley	620	50
Westley	3,236	7
2 miles south of Westley	3,560	60
2 miles south of Westley	1,822	
2 miles north of Patterson	275	55
September 11		
Tracy	2	100
1 mile east of Tracy	68	79
6 miles south of Tracy	2	
2 miles south of Vernalis	116	88
2 miles south of Westley	685	99
September 22		
1 mile east of Tracy	1	
6 miles south of Tracy	2	
5 miles south of Tracy	4	
4 miles north of Vernalis	2	
Westley	12	
2 miles south of Westley	50	100
2 miles south of Westley	2	

TABLE 6

ALFALFA BUTTERFLY LARVAL POPULATIONS AND PARASITISM BY *Apanteles* DURING THE  
MIDSUMMER INFESTATION IN THE NORTHWEST PORTION OF THE  
SAN JOAQUIN VALLEY, IN 1940

Location of field	Total larvae per 100 sweeps	Large larvae per 100 sweeps	Small larvae per 100 sweeps	Per cent of small larvae parasitized
July 9				
Tracy	42	7	35	75
Tracy	5	0	5	100
6 miles south of Tracy	24	0	24	
5 miles south of Tracy	0	0	0	
3 miles south of Tracy	3	0	3	100
7 miles south of Tracy	21	2	19	78
4 miles north of Vernalis	0	0	0	
1 mile south of Vernalis	2	1	1	
2 miles south of Vernalis	15	1	17	12
Westley	4	0	4	100
2 miles north of Patterson	77	4	73	78
1 mile north of Patterson	0	0	0	
Patterson	18	0	18	100
July 22				
Tracy	89	71	18	25
Tracy	375	186	189	50
4 miles south of Tracy	232	1	231	28
6 miles south of Tracy	814	426	388	16
5 miles south of Tracy	2,134	.	.	.
Vernalis	42	2	40	25
2 miles south of Vernalis	43	23	20	25
2 miles south of Westley	645	430	215	16
2 miles south of Westley	900	.	.	..
Patterson	1	1	0	..
July 30				
Tracy	5	2	3	100
Tracy	111	61	50	94
Tracy	160	63	97	89
3 miles south of Tracy	83	21	62	95
4 miles south of Tracy	387	203	184	86
6 miles south of Tracy	804	750	54	25
5 miles south of Tracy	2,016	.	.	.
Vernalis	40	4	36	100
2 miles south of Vernalis	188	81	107	87
2 miles south of Westley	318	300	18	58
2 miles south of Westley	131	.	.	..
2 miles north of Patterson	25	7	18	93
Patterson	1	1	0	..

TABLE 6 (*Continued*)

Location of field	Total larvae per 100 sweeps	Large larvae per 100 sweeps	Small larvae per 100 sweeps	Per cent of small larvae parasitized
August 8				
Tracy . . . . .	18	0	18	92
3 miles south of Tracy	7	1	6	100
4 miles south of Tracy	42	12	30	93
5 miles south of Tracy	16	0	16	100
5 miles south of Tracy	255	195	60	50
6 miles south of Tracy	35	0	35	95
4 miles north of Vernalis	11	0	11	100
Vernalis . . . . .	7	3	4	66
Westley	240	2	238	96
Westley . . . . .	11	1	10	85
2 miles south of Westley	6	0	6	100
2 miles south of Westley	14	6	8	83
August 23				
Tracy . . . . .	1,341	550	791	73
4 miles south of Tracy	148	14	134	92
5 miles south of Tracy	325	0	325	83
6 miles south of Tracy	600	18	582	90
1 mile south of Vernalis	400	200	200	50
2 miles south of Vernalis	690	165	525	42
2 miles south of Westley . . . . .	798	2	796	70
2 miles south of Westley . . . . .	6,300	4,000	2,300	40
2 miles north of Patterson	42	0	42	
Patterson . . . . .	864	450	414	50
September 3				
Tracy . . . . .	315	7	308	99
Tracy . . . . .	2,150	330	1,850	99
4 miles south of Tracy	307	1	306	94
5 miles south of Tracy	1,830	780	1,050	69
5 miles south of Tracy	1,200	100	1,100	88
Vernalis . . . . .	17	0	17	100
2 miles south of Vernalis	540	306	234	92
2 miles south of Vernalis	533	65	468	97
2 miles south of Vernalis . . . . .	287	1	286	100
2 miles north of Patterson . . . . .	151	6	145	97
Patterson . . . . .	86	12	74	94
September 12				
2 miles south of Tracy . . . . .	41	1	40	95
5 miles south of Tracy . . . . .	26	0	26	92
4 miles north of Vernalis . . . . .	21	0	21	80
Vernalis . . . . .	15	0	15	100
2 miles south of Westley . . . . .	6	0	6	100

TABLE 7  
ALFALFA BUTTERFLY LARVAL POPULATIONS AND PARASITISM BY *Apanteles* DURING THE  
MIDSUMMER INFESTATION IN THE NORTHWEST PORTION OF THE  
SAN JOAQUIN VALLEY, IN 1941

Location of field	Total larvae per 100 sweeps	Large larvae per 100 sweeps	Small larvae per 100 sweeps	Per cent of small larvae parasitized
July 17				
1 mile east of Tracy . . . . .	77	22	55	43
1 mile east of Tracy . . . . .	132	66	66	10
4 miles south of Tracy . . . . .	11	4	7	50
5 miles south of Tracy . . . . .	1	0	1	100
6 miles south of Tracy . . . . .	8	4	4	
Vernalis . . . . .	95	44	51	52
4 miles north of Vernalis . . . . .	82	57	25	40
2 miles south of Westley . . . . .	1	0	1	
2 miles north of Patterson . . . . .	584	268	296	19
July 29				
3 miles south of Tracy . . . . .	920	750	140	50
3 miles south of Tracy . . . . .	708	392	314	48
5 miles south of Tracy . . . . .	1,750	1,630	120	12
6 miles south of Tracy . . . . .	736	662	74	64
8 miles southwest of Tracy . . . . .	13,500			
Vernalis . . . . .	80	62	18	47
2 miles south of Vernalis . . . . .	460	378	82	8
2 miles south of Westley . . . . .	1,474	402	1,072	15
Patterson . . . . .	1,784	1,576	208	35
August 6				
1 mile east of Tracy . . . . .	12	0	12	100
3 miles south of Tracy . . . . .	258	194	64	84
4 miles south of Tracy . . . . .	139	1	138	92
5 miles south of Tracy . . . . .	105	4	101	84
5 miles south of Tracy . . . . .	172	148	24	50
6 miles south of Tracy . . . . .	738	610	128	73
1 mile south of Vernalis . . . . .	410	302	108	53
2 miles south of Vernalis . . . . .	124	90	34	88
2 miles south of Westley . . . . .	1,930	1,360	570	72
2 miles north of Patterson . . . . .	2,036	1,812	224	48
Patterson . . . . .	185	80	105	88
2 miles east of Patterson . . . . .	256	160	98	95
August 14				
3 miles west of Tracy . . . . .	61	21	40	94
2 miles west of Tracy . . . . .	104	2	102	93
1 mile east of Tracy . . . . .	133	1	132	98
1 mile east of Tracy . . . . .	43	1	42	100
3 miles south of Tracy . . . . .	101	38	63	85
3 miles south of Tracy . . . . .	172	3	169	99
5 miles south of Tracy . . . . .	83	5	78	96
6 miles south of Tracy . . . . .	80	3	77	97
8 miles southwest of Tracy . . . . .	50	30	20	100
2 miles south of Vernalis . . . . .	264	11	253	83
Westley . . . . .	182	22	160	79
3 miles north of Patterson . . . . .	76	43	33	71
3 miles north of Patterson . . . . .	253	230	28	90
2 miles north of Patterson . . . . .	129	0	129	86
Patterson . . . . .	33	9	24	100
2 miles west of Patterson . . . . .	68	7	61	100

TABLE 7 (*Continued*)

Location of field	Total larvae per 100 sweeps	Large larvae per 100 sweeps	Small larvae per 100 sweeps	Per cent of small larvae parasitized
August 26				
Tracy . . . . .	1,374	16	1,358	88
1 mile east of Tracy . . . . .	527	42	485	84
3 miles south of Tracy . . . . .	547	110	437	67
4 miles south of Tracy . . . . .	2,086	484	1,602	64
6 miles south of Tracy . . . . .	3,203	1,454	1,754	67
2 miles south of Vernalis . . . . .	870	50	820	64
Westley . . . . .	11,336	5,064	6,272	42
2 miles south of Westley . . . . .	874	4	870	97
3 miles northwest of Patterson . . . . .	2,284	516	1,768	42
Patterson . . . . .	1,240	92	1,148	90
September 3				
Tracy . . . . .	1,032	136	896	96
3 miles south of Tracy . . . . .	9,100			
3 miles south of Tracy . . . . .	2,268	1,066	1,200	64
4 miles south of Tracy . . . . .	378	6	372	90
4 miles south of Tracy . . . . .	4,564	1,886	2,676	82
5 miles south of Tracy . . . . .	2,238	700	1,538	16
6 miles south of Tracy . . . . .	2,258	1,296	960	86
Vernalis . . . . .	331	84	247	62
2 miles south of Vernalis . . . . .	1,296	1,140	156	64
2 miles south of Westley . . . . .	2,584	720	2,164	91
2 miles south of Westley . . . . .	2,320	376	1,944	58
2 miles northwest of Patterson . . . . .	1,520	494	1,026	76
Patterson . . . . .	376	16	360	96
September 12				
4 miles northwest of Tracy . . . . .	167	39	128	96
Tracy . . . . .	265	2	263	99
3 miles south of Tracy . . . . .	583	14	569	98
4 miles south of Tracy . . . . .	28	0	28	100
5 miles south of Tracy . . . . .	71	0	71	100
5 miles south of Tracy . . . . .	1,292	736	556	84
6 miles south of Tracy . . . . .	75	1	74	96
Vernalis . . . . .	540	46	494	98
2 miles south of Vernalis . . . . .	480	70	410	95
2 miles south of Westley . . . . .	144	17	127	94
3 miles north of Patterson . . . . .	261	2	259	99
2 miles northeast of Patterson . . . . .	2	0	2	100
2 miles northeast of Patterson . . . . .	255	21	234	98
Patterson . . . . .	908	3	905	98

ronmental resistance is low, an almost unnoticed population of butterflies will give rise to destructive larval populations. If the environmental resistance is high, large numbers of butterflies may not be able to produce enough larvae to do any damage. At times butterflies have been so abundant that stubble fields have appeared as if they were actually moving. In spite of such large populations at the start of a new crop, little damage has been done in certain localities, largely because of *Apanteles*, and the action of the wilt disease.

The factors that make *Apanteles* a very effective parasite are as follows: (1) it has a shorter life cycle than its host; (2) it apparently finds its host with ease; and (3) it destroys its host before it has had an opportunity to do any appreciable damage.

### EFFECT OF THE WILT DISEASE ON THE ALFALFA BUTTERFLY

The importance of the wilt disease in checking the ravages of the alfalfa butterfly has been observed by Wildermuth (1911, 1914, 1916, 1920), Cartwright and associates (1933), and at the Kansas station (1924). Whether the causal agent is a bacterium or a virus is not definitely known. However, Brown (1930) describes a disease of lepidopterous larvae which attacks the alfalfa butterfly and claims the causal organism to be *Staphylococcus flaccidifex* (Glaser). It is not known if this disease is the same as that which occurs in California. Most available information would indicate that it is bacterial in nature.<sup>7</sup> The disease caused the death of the larvae in a very short time. Diseased larvae can usually be first detected when the color turns from the normal green to a paler yellowish or grayish green. Shortly after this stage is reached the caterpillars die, turn dark in color, and wilt down to a watery, decaying mass. The dead caterpillars usually remain clinging to the alfalfa stems and often, where the disease has attacked large populations, the dead caterpillars may be seen hanging from the alfalfa by the thousands. From observations made in the laboratory it appears that once a larva is infected with the disease, its further development may be arrested. It was almost a certain sign that the disease is developing when larvae, being reared under constant temperatures, failed to molt as expected. It is also possible that larvae unusually resistant

<sup>7</sup> A few experiments designed to identify the etiological agent responsible for the disease were carried out by the junior author together with Dr. Michael Doudoroff of the Department of Bacteriology. A gram-positive yellow diplococcus, possibly identical with *Staphylococcus* (?) *flaccidifex* (Glaser) was found present in the intestinal contents and tissues of dying and dead larvae with remarkable regularity, but not universally. When present, it was practically the only organism that could be cultured. However, no bacteria could be isolated from several larvae which had died with similar symptoms, and in two cases only a colorless facultative catalase-negative diplococcus (probably a lactic acid bacterium) was found. Furthermore, the yellow diplococcus was found on several occasions in feces of apparently healthy larvae which later emerged successfully as butterflies, although the intestinal contents of such normal larvae did not show the presence of the organisms to any extent. Fresh feces were also relatively lacking in bacterial flora, indicating a later development of the bacteria. Attempts to infect larvae raised from eggs with pure cultures of the diplococcus by feeding and injection gave no significant results, since a large number of control individuals died of the same or similar disease, and the relative number of survivors were approximately the same for treated and untreated caterpillars. From these observations, it seems likely that the yellow coccus is not the primary causal agent, although the inability to raise healthy larvae made carefully controlled experiments impossible. It would seem that another cause, possibly a virus, must be considered in the etiological studies. Chapman and Glaser (1915) suggested that such a virus might be the causal agent.

may harbor the disease without showing it externally. This may account for the fact that the disease is sometimes carried over into the pupa and the latter stage killed by it.

The disease is beyond doubt one of the most important of the natural checks upon the alfalfa butterfly. Usually two conditions, high humidity and a large host population, are needed before the disease reaches epidemic proportions. Certainly where a destructive population of alfalfa butterfly larvae is developing, a timely irrigation may make the environment very favorable for the development of the disease. Other investigators who mention moisture as favoring the disease are Wildermuth (1911, 1914, 1916, 1920), Cartwright and associates (1933), and the Kansas Agricultural Experiment Station (1924).

In many cases the beneficial action of the disease does not come into play until the alfalfa crop is seriously damaged. In some instances nearly complete defoliation may occur before feeding is checked. However, once started under favorable conditions the disease can destroy the caterpillar population in a remarkably short period. The following will illustrate this. On July 29 in one field there were approximately 14,000 larvae collected per 100 sweeps. At this time the wilt disease was just beginning to appear. Three days later hundreds of thousands of dead worms were observed clinging to the alfalfa, and only 40 live caterpillars were collected per 100 sweeps. Many of these were infected and on August 6, only 13 larvae were collected per 100 sweeps. Most of these had the early symptoms of the disease.

The disease does not always reach epidemic proportions. Cases have been observed where the disease continues to kill enough caterpillars so that the alfalfa can grow and produce a commercial crop. Where this occurs, caterpillars and disease can be found during the entire growth of the crop and, while some damage may be done, the disease saves the crop from total destruction.

The wilt disease gains in importance as the larval population increases. It apparently does not attack the brood of caterpillars that makes its appearance in June, being largely restricted to the midsummer and late summer broods. It becomes the most important natural factor checking the alfalfa butterfly larval population in fields where *Apanteles* is unable to hold the caterpillars in check.

#### THE EFFECT OF THE WILT DISEASE ON APANTELES

From observations in the field it would seem that sometimes the wilt disease has an adverse effect upon *Apanteles*. This appears to be particularly true where the disease is present in epidemic proportions. However, cases have been noted where *Apanteles* has dominated the situation after the wilt disease had first reduced the number of larvae; where this occurred there was no further build-up in the larval population. In fields where the wilt disease is killing off larvae in large numbers, the number parasitized by *Apanteles* is often less than in surrounding fields. The difference may be very noticeable. As an example, on September 3, 1941, in one field where the disease was prevalent only 16 per cent of the small larvae were parasitized, whereas in the surrounding area the amount of parasitism was 82 per cent or higher. The reason for this condition is not known, and one can only speculate concerning the cause.

It is possible that where the wilt disease is present in epidemic proportions it kills off parasitized larvae before the parasite can complete its development. The disease may be spread by the parasite. It may be that the causal organism is carried on the ovipositor. If this is the case the parasite would certainly be working against itself.

In fields where the wilt disease is present but not abundant, *Apanteles* is apparently not very much affected. In such fields it is not uncommon to find nearly all the small larvae parasitized. Where this condition exists it is possible that the two natural factors work independently in reducing the numbers of butterfly larvae—the wilt disease killing the larger larvae, and the parasites, the smaller. If this is the case the danger of *Apanteles* spreading the disease on its ovipositor is not very great, for the investigation indicates that it parasitizes only the first three instars of its host. If the larger larvae are not attacked there will be little danger of the parasite ovipositor becoming contaminated. Also, where the disease is not present in epidemic proportions the danger of the early instar alfalfa butterfly larvae contracting the disease is greatly reduced, and the chances of *Apanteles* becoming contaminated would thus be minimized.

### DISCUSSION

This investigation has shown that there are a number of factors which influence the abundance of the alfalfa butterfly. Beyond a doubt there are many besides those studied that have a bearing upon the alfalfa butterfly population. Before control measures are instituted against the pest, the status of the biological and physical factors should be adequately known. Such knowledge as reported here should certainly be used in planning control of this serious alfalfa pest. The investigation has shown that in the summer there are three more or less definite broods. These broods have occurred in each of the four years that this study has been in progress and this natural phenomenon can be utilized in controlling the pest. If fields are closely observed, cutting might be planned so that the alfalfa would be in stubble during the periods of rapid build-up of larval populations, and would be making growth when the pest population is small.

All observations would indicate that the amount of damage done by later broods is linked with the first summer brood. If the parasitism is low at the time of the first summer brood and other conditions are favorable, a relatively large adult population will develop with few parasites to prey on it, and there is every likelihood that destructive populations will occur later in the summer. It seems, therefore, that everything possible should be done to restrict the size of the first brood. The alfalfa crop should be as carefully watched as any other crop and cut immediately as soon as mature. During the 1941 season, at this critical period, alfalfa fields were not irrigated in certain localities so that the water could be made available for the irrigation of beans. Because of this, the alfalfa grew slowly and in some fields as much as 7 weeks passed before it could be cut. In such fields, where the environmental resistance to the butterfly was low, extremely large populations of the butterfly larvae completed their development. Had these fields received proper care, it is likely that the damage caused by later infestations would have been considerably reduced.

## ACKNOWLEDGMENTS

It is with sincere pleasure that the authors express appreciation to Professor Harry S. Smith, Professor G. F. MacLeod, and Professor E. O. Essig for the helpful criticism they have given during the progress of these investigations. The authors are also indebted to Dr. S. E. Flanders for numerous suggestions, and to Dr. C. F. W. Muesebeck and Mr. P. H. Timberlake for the identification of *Apanteles flaviconchae*; thanks are also due Miss Elizabeth Truesdell, who was of much assistance in helping to assemble the data presented.

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# H I L G A R D I A

*A Journal of Agricultural Science Published by  
the California Agricultural Experiment Station*

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VOL. 15

OCTOBER, 1948

No 5

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## THE CALIFORNIA STATE LAND SETTLEMENTS AT DURHAM AND DELHI<sup>1, 2, 3</sup>

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### INTRODUCTION

THE OBJECTIVES of this study have been to discover and analyze the problems that were encountered in the California State Land Settlements at Durham and Delhi. The study has been made because of current settlement activity by various governmental authorities and because it is believed that the California settlements contain in their history information which should be of value to those who are interested in such activities. The leader of the California program was the outstanding authority in the field. The plans involved were of a fundamental and important character. The problems encountered were varied and difficult.

No attempt has been made here to compare these settlements with any others. In particular there is no comparison of governmental projects with private projects. Any such analysis would require a study of far larger scope than that which has been attempted here. This is a case study, and such generalizations as are made are due to the nature of the particular data or problem concerned and do not apply generally to various methods of land settlement.

### BACKGROUND AND OBJECTIVES

In 1917 the State of California initiated a land-settlement program designed to improve the methods then in use and to encourage further developments.<sup>5</sup> Under a land-settlement act, two settlements were established, one at Durham with about 130 settlers, and one at Delhi with about 230 settlers. (For location, see inset map, fig. 3, p. 412.)

While the settlements were later intended to be the beginning of a permanent and large-scale activity, the immediate purpose of the initial act was to

<sup>1</sup> Received for publication March 11, 1942.

<sup>2</sup> Paper No. 109, The Giannini Foundation of Agricultural Economics.

<sup>3</sup> The author wishes to take this opportunity to thank the many people who have aided him in the study. Members of the University staff, those who were associated in the administration of the settlements, the settlers, and others have given liberally of their time and information. While space forbids listing them, the author wishes to emphasize that the study would not have been possible without their cooperation.

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<sup>5</sup> California Statutes, 1917. Chap. 755. A copy of the act may be found in the Appendix of: Mead, Elwood. *Helping men own farms.* (Cited in footnote 8.)

demonstrate desirable land-settlement methods.<sup>6</sup> In the past, the development of agriculture generally had been largely in private hands and its history had been clouded with many mistakes. The following paragraphs are descriptions of the situation as given by different authorities.

If a person owns a ranch that is profitable he is not generally anxious to sell it. If a man owns a herd of cows and desires to sell some of them he will, if he is a good business man, seek to sell his poorest cows. Land follows the same economic law. The ranches that come upon the market are apt to be those that have for some economic law become unprofitable....

It is a characteristic of California conditions that its soils are what is called "spotted." There may be very poor areas surrounded by land of great fertility. Men who make it a business to buy and subdivide land will find these less fertile areas offered for sale at much less than the ordinary run of land. For this reason, such areas are often chosen for subdivision. Doubtless the men who purchase these tracts for subdivision are not infrequently mistaken as to their real value, or at least do not appreciate the actual difference in productivity between lands of different qualities.<sup>7</sup>

In the past, private colonizers have given little thought to the need of settlers. ... Their ability has been mainly shown in writing alluring advertisements and working out selling devices. Too often the main appeal has been to the American passion for speculation. Clerks, artisans, and business men who knew nothing of farming and never expected to farm, have bought farming areas not to live on them and cultivate them, but to share in the increment which the development by others would bring....

In one noted instance, eastern farm buyers were shown land that two years before had been bought for \$7.00 an acre. They were told this and also told that the present price was \$200.00 an acre; and they were advised to buy because next year it would sell for \$400 an acre. This did not seem impossible; for the air was full of stories of money made out of land deals. Many who bought took a profit if there was a rise. If the land could not be sold at an advance, they lost the first payments and the land reverted to the colonizers.<sup>8</sup>

In another district a tract of "goose" land sold one year for \$5.00 an acre, the next year for \$15 an acre, and was then subdivided and sold as garden soil for \$125 an acre. Three brothers who were market gardeners bought farms there and moved on with their families. They found when the soil was wet it was a quagmire and when it was dry it could only be cultivated with dynamite. In three years time they had not raised enough to keep a goat alive and had to abandon their homes, losing their money and time and carrying with them a bitter feeling of injustice and wrong.<sup>9</sup>

Relatively few of the men engaged in this business were knowingly dishonest, but the majority of them were unthinking and ignorant. They did not know, nor did they apparently care to know, how settlers were to obtain money needed to improve and equip the farms sold them or how they were to earn a living income. The prosperity of the settler was his own affair. The land agents' business was to make money out of him rather than to make money for him.<sup>10</sup>

This last quotation is from the report of the California Commission on Land Colonization and Rural Credits which, under authorization of the 1915 Legislature, had been appointed by Governor Hiram W. Johnson to investigate the land-settlement and rural-credits situation in the state.<sup>11</sup> The commission

<sup>6</sup> California Commission on Land Colonization and Rural Credits. Report of the Commission on Land Colonization and Rural Credits of the State of California, November 29, 1916. p. 85. 1916.

<sup>7</sup> California State Land Settlement Board. Report of the State Land Settlement Board of the State of California, June 30, 1918. p. 5 and 27. 1918.

<sup>8</sup> Hunt, Thomas Forsyth, and other members of the staff. Some things the prospective settler should know. *California Agr. Exp. Sta. Cir.* 121:15-16. 1914. (Out of print.)

<sup>9</sup> Mead, Elwood. Helping men own farms. p. 1-228. The Macmillan Co., New York, N. Y. 1920. (See especially p. 98.)

<sup>10</sup> California Commission on Land Colonization and Rural Credits. Report . . . op. cit. p. 52.

<sup>11</sup> *Ibid.* p. 50.

<sup>11</sup> California Statutes, 1915. Chap. 279.

toured the state and collected data on conditions found in many different areas. They visited a number of subdivision projects and had reports presented to them on the various factors that brought success or failure. A large number of items such as soil, size of farm, tenure, coöperation, farm labor, and availability of land, received attention. They gave particular attention to speculation and credit. Speculation was deplored as a detrimental activity. As to credit, they found that the average rate of interest on contracts was 6.9 per cent and on bank and private loans 8.0 per cent; both were regarded as much too high. The average time of repayment, 5.8 years, was too short. Very often the buyers' ready cash was used up in making the first payment, and it was extremely difficult to meet payments in the first years of development.<sup>12</sup> The commission concluded as follows:

.... in California the settler who has not had a large cash capital or some outside income has not been able to purchase a farm. We have not found a single settler who, bringing with him only the limited capital accepted by state systems in other countries, has been able to pay for his land in the time agreed upon in his contract.<sup>13</sup>

The commission found that a large proportion of settlers in California were failures. Of those who prospered, many did so by speculative price changes, the profits of which were often used in further speculation. In any case, the cost of selling the land, estimated to be as much as one fourth the selling price, was a heavy load for the settler.<sup>14</sup> The commission reported, moreover, that these faults were unnecessary, that they could be corrected by better methods, particularly under state aid and direction.

Among the features open to correction, the commission thought that none were more important than liberal credit and claimed that:

Some credit system more liberal than that of the Federal Farm Loan Act or that provided by colonization enterprises is therefore indispensable ....<sup>15</sup>

In particular, the commission stressed the need for long periods of repayment, even to requiring no payments of principal during the first two years.<sup>16</sup> They also emphasized the need for making loans on a larger percentage of the appraised value, loans up to 95 per cent being advised for land.<sup>17</sup>

Another essential need suggested was for the state to provide settlers with technical services from the College of Agriculture and other governmental agencies. Soil and crop specialists were to choose the land, judge its character, determine its crops, and decide whether it was worth subdividing. The settler was to be given all the information available concerning the value and productivity of his farm.<sup>18</sup>

The report of this commission was an important step in the adoption of a settlement program by California and, in many respects, was a comprehensive

<sup>12</sup> The evidence presented on the inability of settlers to meet payments in early years seemed to be particularly strong if orchards were planted.

<sup>13</sup> California Commission on Land Colonization and Rural Credits. Report .... *op. cit.* p. 19. See also: Breed, A. H. The land settlement bill. p. 1-10. Sacramento, 1917. [Argument presented to California Senate by author of settlement act.] (Files of Giannini Foundation.) As indicated in this quotation, a contrast was repeatedly drawn between the land-settlement systems of other countries and the system in the United States.

<sup>14</sup> California Commission on Land Colonization and Rural Credits. Report .... *op. cit.* p. 37 and 53.

<sup>15</sup> *Ibid.* p. 28.

<sup>16</sup> *Ibid.* p. 84.

<sup>17</sup> *Ibid.* p. 86.

<sup>18</sup> *Ibid.* p. 54 and 86.

statement of the problems involved. Some features, however, which were thought to be desirable became apparent only as the settlement program actually got under way. The California State Land Settlement Board was created to administer the new program and in an early report stressed the advantages, for instance, of organization on a community basis. The statement was as follows:

It will be far easier for the people in this colony who are all making the same struggle, all faced by the same problems and all required to live in about the same way, to succeed, than it would be if they were scattered through different communities and surrounded by neighbors who either owned their farms or who were not trying to accumulate money to pay for one. The fact that all these settlers are in debt, that they are all compelled to work hard and be careful and saving is a source of strength to the less experienced members of the colony, and especially to those who lack strength of purpose.<sup>19</sup>

Integral parts of this community life were coöperation and social organization. Supplies would be purchased, produce sold, and even some production phases of the farm work carried on under coöperative methods. In this way some of the industries of the countryside could be brought back, farmers could regain control of the sale of their products, economies could be achieved, and morale would be kept high.<sup>20</sup>

To make success more nearly certain, each settler would be chosen with great care, attention being given not only to his capital but to his experience, training, family, interests, and general attitude toward farming and toward co-operative effort. He would have to appear before the Board or other officials for questioning and only if he showed promise would he be accepted.<sup>21</sup> This attention was to continue after the settler had taken over his farm. The policy of direction was described as follows:

The act provides for the employment of a farm advisor who will also be a business manager for the board. He will be on the ground observing how settlers cultivate their farms and noting who are industrious and who are idle and unworthy of financial aid. The presence and the influence of this practical guide will save many settlers from mistakes which would be costly. It will enable the board in dealing with settlers to discriminate between those deserving aid and the shiftless who would misuse it. The prompt and summary elimination of the latter is essential because of the demoralizing influence they may exert. Generous aid for the worthy and unsparing exposure of those who seek to abuse the state's interest will have great influence in promoting a spirit of community pride that, as a rule, is lacking in individualistic colonies. It will encourage the formation of an intelligent, coöordinated community life, whose object will be not simply to make money, but to realize the best there is in modern civilization.<sup>22</sup>

**That the Board had the power to carry out its program of control is made clear in the law which provided that:**

In the event of a failure of a settler to comply with any of the terms of his contract of purchase and agreement with the board, the state and the board shall have the right at its option to cancel the said contract of purchase and agreement and thereupon shall be released from all obligation in law or equity to convey the property and the settler shall forfeit all

<sup>19</sup> California State Land Settlement Board. Information regarding progress under the land settlement act of the State of California and about the plans for soldier settlement in the future, May 30, 1919, p. 20. 1920.

<sup>20</sup> Mead. *Helping men own farms*. *op. cit.* p. 140-61.

<sup>21</sup> California Statutes, 1917, Chap. 755, Sec. 16.

<sup>22</sup> Mead, Elwood. Government aid and direction in land settlement. *Amer. Econ. Rev.* 8(1) Sup.: 81. March, 1918.

right thereto and all payments theretofore made shall be deemed to be rental paid for occupancy.<sup>23</sup>

No further details regarding the plan of settlement will be presented here since they will be better described later in the study. It must be emphasized, however, that the proponents were enthusiastic in their support of the program and were confident of success. Even at the start of the Durham settlement, they thought of the program as a demonstration of tried and proved methods and expressed themselves as follows:

The adoption of this policy . . . will not . . . be an experiment. It has been a financial and economic success in the thickly populated countries of Europe and in the sparsely populated countries of Australia and New Zealand.<sup>24</sup>

That the proponents also believed that their program was of the greatest importance is made clear in the following statements:

The colonization and development of the unpeopled farm land of California is of such importance to all the people of the state that it should not be left to the separate action of landowners, but should be shaped in part by the carefully thought out purposeful action of all the people. This means that the state should have a land settlement policy and deal with this matter as a public problem.<sup>25</sup>

It is to the interest of the whole state that its fertile lands should be cultivated and that active colonization should be promoted.<sup>26</sup>

Increasing the number of people on farms and improving their living conditions were fundamental aims,<sup>27</sup> which were reëmphasized when the war ended and ex-soldiers began to look for work. Here was an army of men to be placed. Farm life was regarded as particularly desirable for them.

These objectives were attainable, the proponents believed, because they thought there were available large acreages of fertile but unfarmed land. The California Commission on Land Colonization and Rural Credits described this situation as follows:

The state has an immense area of fertile and unpeopled land. Only eleven million acres out of the twenty-eight million acres are being cultivated. . . .

. . . great properties, owned by non-residents, are being cultivated by tenants or by nomadic and unsatisfactory hired labor. These great properties ought to be subdivided and cultivated by residents. From statistics furnished by C. L. Seavey, tax commissioner, it appears that 310 landed proprietors own over four million acres suited to intensive cultivation and capable of supporting a dense population. This would make 100,000 forty-acre farms. One firm owns nearly one million acres; one railroad owns 500,000 acres. In Kern County four companies own over 1,000,000 acres, or more than half the land in private ownership. The Kern County Land Company alone owns 356,000 acres. In Merced County Miller and Lux own 245,000 acres. The evils of such ownership are every year becoming more apparent. We have at one end of the social scale a few rich men who as a rule do not live on their estates, and at the other end either a body of shifting farm laborers or a farm tenantry made up largely of aliens, who take small interest in the progress of the community. Political stability, the best results in agriculture, and satisfactory social conditions require that

<sup>23</sup> California Statutes, 1917. Chap. 755, Sec. 22.

<sup>24</sup> Mead. Government aid and direction in land settlement. *op. cit.* p. 76.

<sup>25</sup> California Commission on Land Colonization and Rural Credits. Report . . . *op. cit.* p. 82.

<sup>26</sup> *Ibid.* p. 7.

<sup>27</sup> Mead. Helping men own farms. *op. cit.* p. 10.

Mead, Elwood. Placing soldiers on farm colonies. *Ann. Amer. Acad. Polit. and Social Sci.* 81:63. 1919.

this inheritance from a Mexican land system and former land laws of the United States be abolished.<sup>28</sup>

The proponents of state action planned to bring about rapid development of these areas. (For the extent of their program see p. 410.) Moreover, they not only believed that there was land available but also that there was a need for more farm products. They described the situation as follows:

The state now buys a large part of its meat and many other farm products abroad. Increased production would lessen the cost of living and keep at home money now sent to other sections to pay for food products.<sup>29</sup>

....this nation is faced with a shortage of food and how to obtain three square meals a day is becoming a vital problem.<sup>30</sup>

The lack of population which was believed to exist in agriculture was explained in part by the attractions of the city and in part by improper conditions in the country. Dr. Elwood Mead, Chairman of the California Commission on Colonization and Rural Credits, described the situation as follows:

The main reasons.... are the high wages and easy conditions of labor in cities and the obstacles which high land prices and high rents present to men who seek to become farm owners. When Henry Ford made \$5.00 a day the minimum wage for unskilled workers for his factory, he started a competition for labor that the farmer could not meet.<sup>31</sup>

People cannot be kept on the land where non-resident ownership and tenantry prevail. Nothing short of ownership of the land one toils over will suffice to overcome the lure of the city. At any sacrifice, at any cost, the people who farm the land must be enabled to own it. On such ownership the life of a modern nation may depend.<sup>32</sup>

The proponents of land settlement not only wished to encourage the development of the small family-owned farm, they also proposed to establish homes for farm laborers whose position was deplored by Dr. Mead as follows:

In no particular is there greater need of change in American rural life than in the present position and treatment of the American farm laborer. The American farm of the future has special need for intelligent, dependable, trained men, who are willing to work for wages. They are as essential to the success of agriculture as are our farm owners. Furthermore, unless American democracy is a sham there is the same need for insuring that the family of the farm laborer shall live a comfortable, independent life, with opportunities for education and intellectual development, as there is for insuring these advantages to the farm owner. It was not necessary during the era of free land to pay much attention to this matter. Good laborers remained on farms until they could save money to become owners. They were recognized as the social equal of farm owners. But these conditions are gone. The American farm laborer now lives, as a rule, in a bunk-house; he has no social status, and competes with the Asiatic and the peon and degenerates into a hobo. If he is married it is rare that a home is provided close to his employment, and he is usually separated from his family for long intervals, which is bad for the family, bad for the laborer, and bad for society.

The result is that the intelligent and aspiring American who cannot afford to own land is leaving the country and going to the city; and the social conditions of the farm are suffering.<sup>33</sup>

<sup>28</sup> California Commission on Land Colonization and Rural Credits. Report . . . . *op. cit.* p. 7-8.

<sup>29</sup> *Ibid.* p. 7.

<sup>30</sup> Mead, Elwood. How California is helping people own farms and rural homes. California Agr. Exp. Sta. Cir. 221:1. 1920. (Out of print.) (The reader should recall that this was written just at the end of World War I.)

<sup>31</sup> *Ibid.* p. 1.

<sup>32</sup> Mead. Helping men own farms. *op. cit.* p. 10.

<sup>33</sup> Mead. Government aid and direction in land settlement. *op. cit.* p. 79.

Thus the laborer was to have a home where he could live with his family and employ his time profitably when not working for wages. By keeping a garden, a cow, some pigs, and poultry, he could reduce the cost of living. Most important a home of their own would make the laborer and his family independent and self-respecting. White Americans would be attracted by such a life. The land-settlement program was thus designed to be an aid in building up a "commonwealth of independent white farmers and laborers."

The proponents of the California State Land Settlement Act were not alone in their belief in these objectives. President Theodore Roosevelt in appointing the Commission on Country Life said that:

.... the permanent greatness of any state must ultimately depend more upon the character of its country population than upon anything else.<sup>34</sup>

This commission in their report claimed that there were many possibilities of development of agriculture. Their statement follows:

According to the reports of the United States Geological Survey, there were more than seventy-five million acres of swamp land in the country, the greater part of which are capable of reclamation at probably a nominal cost as compared to their value. It is important to the development of the best type of country life that the reclamation of the lands in rural regions proceed under conditions insuring their subdivision into small farm units and their settlement by men who would both own them and till them. .... As a rule they are extremely fertile. They are capable of sustaining an agricultural population numbering many millions; and the conditions under which these millions must live are properly a matter of national concern.<sup>35</sup>

Many of these objectives, moreover, were becoming concrete reality in the work of the United States Reclamation Service. The Reclamation Act had been passed in 1902 and by 1917 one million acres were being irrigated in projects developed by the Service. The proponents of the California program, such as Dr. Mead, however, claimed that the federal program was not adequate. He said that little distinction was made between good and bad land. Estimates of the probable cost of improving and equipping a farm were not made or were insufficient. The land was not made ready for the application of water—as essential a part of reclamation as the building of canals and reservoirs. Settlers were not chosen on the basis of either personal qualities or capital. The settler was left to himself in planning and building his house and barn, in choosing livestock and equipment, in selecting crops, and in determining cultural practices. All of this took valuable time, made the farm development slow and wasteful, and often meant that the settler failed. Dr. Mead summed up his criticism as follows:

There is so much that is admirable in the Reclamation Act and in the manner in which its engineering and operative features have been carried out that one is reluctant to call attention to its vital defects. But the part which is good only emphasizes the part which is hopelessly bad.

The engineering requirements of the Reclamation Act were carefully thought out; the agricultural and economic needs of settlers were ignored. The things needed to create values in land were provided; the safeguards which would insure those values going to the right people were overlooked.<sup>36</sup>

<sup>34</sup> Anonymous. Report of the Commission on Country Life. p. 43. Sturgis and Walton Co., New York, N. Y. 1917.

<sup>35</sup> *Ibid.* p. 63.

<sup>36</sup> Mead. Government aid and direction in land settlement. *op. cit.* p. 85.

In order to correct this situation the California State Land Settlement Act provided that the engineers not only were to build reservoirs and canals but also were to develop the farms and the community. The settler was not to toil for years getting his farm in shape but was to have this work done properly for him, at least in part, before he arrived.

Dr. Mead had long been regarded as an outstanding authority on irrigation and settlement matters and was in an excellent position to describe the work of the Reclamation Service because in 1915, as chairman of a Central Board of Review, appointed by the Secretary of the Interior, he had spent several months investigating the situation he described. In fact his life had been devoted to similar studies. As early as 1889 he had sponsored the reform of irrigation laws in various western states. From 1899 to 1907 he had headed the irrigation and drainage investigations of the United States Department of Agriculture. From 1901 to 1907 he had served as Professor of Institution and Practice of Irrigation at the University of California. In 1907 he had been invited to Australia as chairman of the Rivers and Water Supply Commission for the State of Victoria. While in Australia he had kept in close touch with the United States and had encouraged an interest in land settlement among friends here, notably Professor Thomas Forsyth Hunt, later Dean of the College of Agriculture, University of California. In 1915, Dean Hunt, because of his interest in the subject, established in the College of Agriculture a Division of Rural Institutions and invited Dr. Mead to be its head. In this Division, among other subjects, the philosophy and practice of land settlement were to be studied and taught.

Because of his experience, Dr. Mead was selected as chairman of the new California State Land Settlement Board, which the Legislature created in 1917. The other members appointed by Governor William D. Stephens were Mr. Mortimer Fleishhacker, a leading financier on the Pacific Coast; Mr. Prescott F. Cogswell of El Monte, an able and successful business man and farmer; Judge William H. Langdon, lawyer and farmer; and Senator Frank P. Flint, another well-known financier.<sup>27</sup> While the Board, owing to a technical change in administrative organization, did not function from 1921 to 1923, Dr. Mead continued as responsible head of the administration until 1924.<sup>28</sup> To simplify the presentation, the Board will be referred to throughout the entire period of state activity as the responsible administrative body.

<sup>27</sup> Mead, *Helping men own farms*, *op. cit.* p. 107.

<sup>28</sup> Specifically, in 1921 the Legislature created a Division of Land Settlement in the Department of Public Works. The original organization was reestablished in 1923. (California Statutes, 1921, Chap. 607. *Also see:* California Statutes, 1923, Chap. 411.)

## INITIAL DEVELOPMENT

### DURHAM DEVELOPMENT

The first task of the California State Land Settlement Board was to secure suitable land. The method used was to advertise for offers. Then the Board, aided by technical experts, considered each tract offered and made recommendations. The Dean of the College of Agriculture set a price for the piece of land selected as most desirable; the Board then negotiated for the purchase.<sup>38</sup>

The purchase at Durham, made early in 1918, was in the main of two tracts, one owned by Judge C. F. Lott, and the other by Stanford University. Mr. Richard White, an attorney at Chico, had an option on the Lott tract and asked \$165,000 for it. The Board fixed \$156,610 as their maximum and for a time it appeared that no deal could be made. Finally the Chico Business Men's Association raised the difference of \$8,390. The Board paid cash for this land. The Stanford land cost \$386,109. The Board paid 10 per cent as a down payment and amortized the remainder in forty semiannual payments at 5 per cent interest. Altogether 6,240 acres were purchased. The improvements were valued at about \$40,000 and consisted largely of buildings. Part of the Stanford land west of Butte Creek, having been leased until 1922, was reserved from immediate settlement.<sup>39</sup>

Figure 1 is a soil map of the settlement area. This was prepared by the University of California Division of Soil Technology. The survey, made in the spring of 1918, was not available at the time of purchase. In its principal features, however, it resembles the Reconnaissance Soil Survey of the Sacramento Valley of 1913. Any differences are caused by the more detailed nature of the Durham survey. Of the three general areas that may be noted, the first is a rough stony area in the northeast, made up of Aiken stony clay loam, Tuscan clay loam, and similar soils. This land, having no value except as pasture, was appraised as such and was, in general, not subdivided. Parts immediately adjacent to the farms were sold very cheaply as pasture, the rest was leased to those who needed extra feed. The second area was the Vina clay adobe and related soils in the southern section. The third area was made up of Vina fine sandy loams, Vina loams, Vina clay loams, and related types.

As soon as the purchase of the tracts had been arranged, the engineers began planning the irrigation system and the subdivision. Mr. Milo B. Williams, an experienced irrigation engineer, was in charge of construction. Mr. George C. Kreutzer was made permanent superintendent. He had done similar work in Australia and had also been a farm advisor in California. A small but efficient irrigation system was built which brought water from Butte Creek and which in most years furnished sufficient water at 50 or 60 cents an acre. Figure 2 shows the subdivisional plan as it existed in 1924. Farms are numbered and laborers' allotments are lettered. Most of the tract was divided into farms with

<sup>38</sup> California State Land Settlement Board. Information for landowners. Cir. 1:1-4. September, 1917.

California State Land Settlement Board. Report . . . June 30, 1918. *op. cit.* p. 7.

<sup>39</sup> California State Land Settlement Board. Report . . . June 30, 1918. *op. cit.* p. 22.

Furlong v. White. (1921) 51 Cal. App. 265. Appellate Records. Third District. Civil 2267. (See especially appellant's opening brief, p. 1-28; and reply brief of respondents, Elwood Mead *et al.*, as members of and constituting the State Land Settlement Board, p. 1-42.)

the greater number varying in size from 20 to 80 acres. A few were smaller and those on poorer soil were larger. The farms on the adobe land consisted of two blocks each, one of adobe and a small one of the better soils. Allotment 35A, for instance, included allotment 35; allotment 19A included 19, and so on. This combination of two soil types, it was thought, would permit a diversified crop plan. Twenty-six farm laborers' allotments were laid out of from 0.4 acre

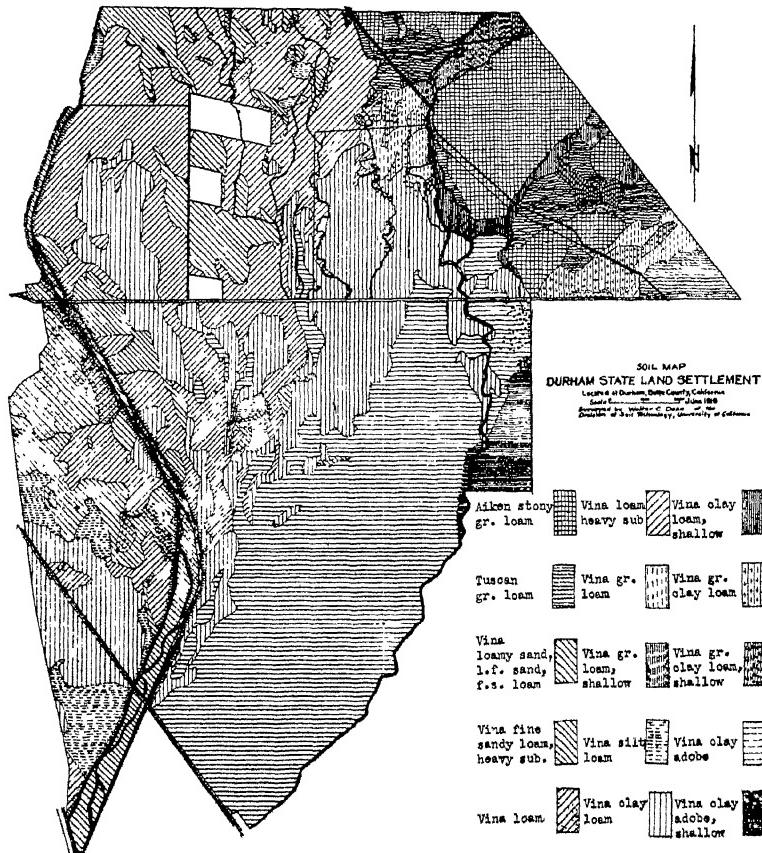


Fig. 1.—Copy of soil map, Durham State Land Settlement, June, 1918.

to 2.4 acres. Allotments 43A, 43B, 44, and some other small areas were reserved for administrative purposes. Allotment 17, centrally located and covered with beautiful old oak trees, was reserved for social use.

In order that all the allotments would be equally desirable, the possibilities of each one were analyzed so that the price set reflected the character of the allotment in relation to the price asked for the other places. The price asked for all the allotments was to total enough to cover the cost of the land to the Board, of improvements made by the Board, and of administration.\*

\* California Statutes, 1917, Chap. 755, Sec. 17.

In carrying out the program, the Board made considerable use of the technical aid which was available. The University of California Division of Soil Technology reported on soils and drainage conditions. The Division of Irrigation Investigations and Practice studied the suitability of the land for irrigation, the cost of constructing irrigation works, and the availability of water. The Division of Entomology and Parasitology surveyed health conditions,

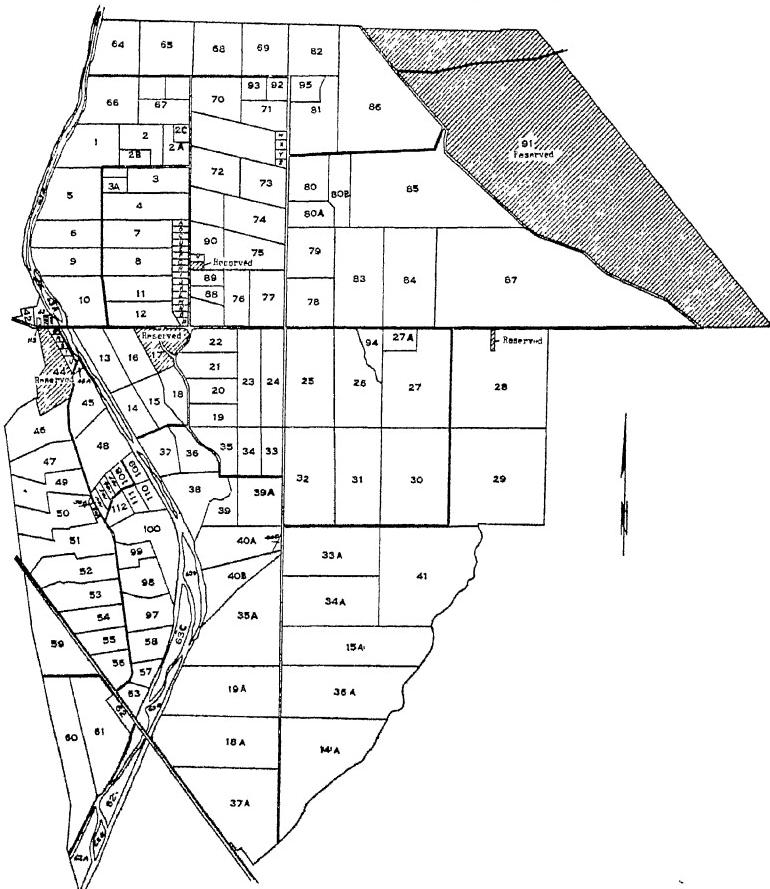


Fig. 2.—Subdivision map, Durham State Land Settlement, April, 1924.

particularly the problem of malaria. The Division of Horticulture reported on the prospect for fruit trees. Other divisions also made reports. Farm advisors were consulted.<sup>42</sup> The State Water Commissioner aided in investigating the

<sup>42</sup> The College of Agriculture gave every help. One view of the relation between the College and the Board was as follows: "The Land Settlement Board is nominally an independent body, but is really an agency of the Agricultural College." (California Commission of Immigration and Housing. A report on large landholdings in southern California with recommendations. p. 37. 1919.) This view, however, does not seem to be justified, though the two organizations coöperated in many ways. Dr. Mead, for instance, was employed and paid by both organizations and divided his time between them.

water supply and the Attorney General investigated land titles and obtained a settlement of a long-standing dispute over water rights on Butte Creek.<sup>43</sup> The United States Department of Agriculture Bureau of Public Roads and Rural Engineering, assisted in preparing a contour map.<sup>44</sup>

The first allotments were offered for sale on May 15, 1918, and almost all of them were immediately taken. Only a few remained unsold.<sup>45</sup> Since the administration had put in a crop that spring on all land ready for planting, the settlement appeared to develop very rapidly. From the very first it was regarded as completely successful. Dr. Mead, enthusiastic over the program, described its importance as follows:

Before the first settlement at Durham was a year old, it had been visited and studied by officials of ten American States and five foreign countries. It was made the basis of Secretary Lane's plans for soldier settlements. It has affected vitally many men who have been coming to Durham constantly to learn what they should do in their private colonization schemes. With the passage of the Act, the state entered on a new economic era.<sup>46</sup>

Because of the rapid development at Durham, the proponents decided to enlarge their program. Durham was intended to be only a demonstration in desirable land-settlement methods, but when Delhi was started the two were thought of as the beginning of a permanent and large-scale state activity. The Board in its first official report made the following recommendation:

The next legislature should amend this act and greatly broaden its scope. It was passed as an educational measure and its operation confined to narrow limits which will have been reached before the legislature adjourns. Land settlement should now be made a permanent feature of state activity.<sup>47</sup>

The Legislature in 1919 approved the recommendation and appropriated a million dollars for immediate work.<sup>48</sup> The Legislature also proposed a ten-million-dollar bond issue for a revolving fund.<sup>49</sup> This issue was not voted on because the legislation was rendered void by the California Supreme Court for technical reasons.<sup>50</sup> It might be noted here that in 1921 the Legislature approved a bond issue for three million dollars, but in the 1922 election this was rejected.<sup>51</sup> In 1923 Dr. Mead proposed a twenty-million-dollar issue but could obtain no political support.<sup>52</sup>

#### DELHI DEVELOPMENT

Most of the acreage at Delhi was bought in November, 1919, from Mr. Edgar M. Wilson of San Francisco. Part of it was owned outright by Mr. Wilson and part by a syndicate in which he had the largest interest and for which he acted as agent. The price for 7,654 acres was \$92.50 an acre. The agreement called for one-third cash on the farm land and all cash for the Delhi townsite and

<sup>43</sup> California State Land Settlement Board. Report of the State Land Settlement Board of the State of California, September 30, 1920, p. 71. 1921.

<sup>44</sup> Further details may be found in the various reports of the Board and in mimeographed reports of the various people concerned. (Files of Giannini Foundation.)

<sup>45</sup> California State Land Settlement Board. Report . . . June 30, 1918. *op. cit.* p. 11.

<sup>46</sup> Mead. *Helping men own farms.* *op. cit.* p. 10.

<sup>47</sup> California State Land Settlement Board. Report . . . June 30, 1918. *op. cit.* p. 27.

<sup>48</sup> California Statutes, 1919. Chap. 450.

<sup>49</sup> *Ibid.* Chap 540.

<sup>50</sup> *Hatfield v. Jordan* (1920). 183 Cal. 223.

<sup>51</sup> California Statutes, 1921. Chap. 738.

<sup>52</sup> Mead, Elwood. Letter. March 1, 1923. (Files of Giannini Foundation.)

certain other small areas. Some small acreages not included in the original deal were purchased later to round out the settlement. They included about 750 acres and varied in price from \$100 to \$233 per acre.

The tract lay 6 miles south of Turlock, principally between the Southern Pacific and Santa Fe railroads, and was cut through by the state highway. The climate was healthful, and the tract adjoined some of the more prosperous areas in the San Joaquin Valley. Water could be obtained from the Turlock Irrigation District, which was one of the best in the state and assured a plentiful supply.

Mr. Williams was again in charge of construction. For superintendent, the Board appointed Mr. Walter E. Packard who had been Assistant State Leader of farm advisors in California and Superintendent of the Imperial Valley Field Station. The technical aid which was made use of at Durham was also used at Delhi.

The 1922 subdivision plan is shown in figure 3. The farms averaged 28 acres in size. Laborers' allotments had sold so well at Durham that at Delhi the board authorized twice as many, relative to the number of farms. In all, about 66 laborers' allotment contracts were made at Delhi. There were also more than 50 poultry allotments, varying in size from 3 to 13 acres, approximately.

To facilitate irrigation installation and settlement, the land was divided into four units. The part that could be developed most easily was to be piped first, and the rest was to follow as rapidly as the engineers could economically proceed. Piping in the first and second units was largely completed during the winter of 1920-21; in the third unit during the winter of 1921-22; in the fourth, or Ballico unit, in part during the winter of 1922-23, and a little more, 15,000 feet, during the winter of 1923-24.

*The Irrigation System.*—The irrigation system at Delhi was a rather elaborate one and, together with leveling, was perhaps the most important item of expense. An estimate had been made of the cost in 1918, at the time when the tract had been first offered to the state. When the land was again considered in 1919, this estimate was revised to take account of price changes.<sup>53</sup> Since, according to this report, only some 1,500 acres could be irrigated by gravity, and since the soil was porous and the topography was rolling, pumping plants and a concrete-pipe-distribution system were advised. The estimated per-acre cost, as of August, 1919, of the pipe-distribution system and pumps installed was \$29. The cost of leveling land for alfalfa plus farm-service ditches, structures, and pipe lines was put at \$40. These two items totaled \$69 per acre.

Once on the land, however, the engineers concluded that more extensive piping was necessary, and in consequence, pipe was installed for most of the farm laterals. While the estimates included 26 miles of concrete pipe from 42 to 18 inches in size, the installation as of June 30, 1923, included 143 miles of pipe from 30 to 6 inches in size.<sup>54</sup> Naturally this new plan brought about a great change in the cost of farm laterals which eventually averaged \$54 an

<sup>53</sup> Williams, M. B. Preliminary report on proposed irrigation and subdivision of a portion of the Wilson tract, Merced County, California. p. 1-7. January, 1918, and August 22-27, 1919. (Typewritten; in files of Giannini Foundation.)

<sup>54</sup> Brown, L. N. [Report of engineers to California State Land Settlement Board relative to cost of irrigation system as of June 30, 1923.] March 26, 1924. (Typewritten; in files of L. N. Brown.)

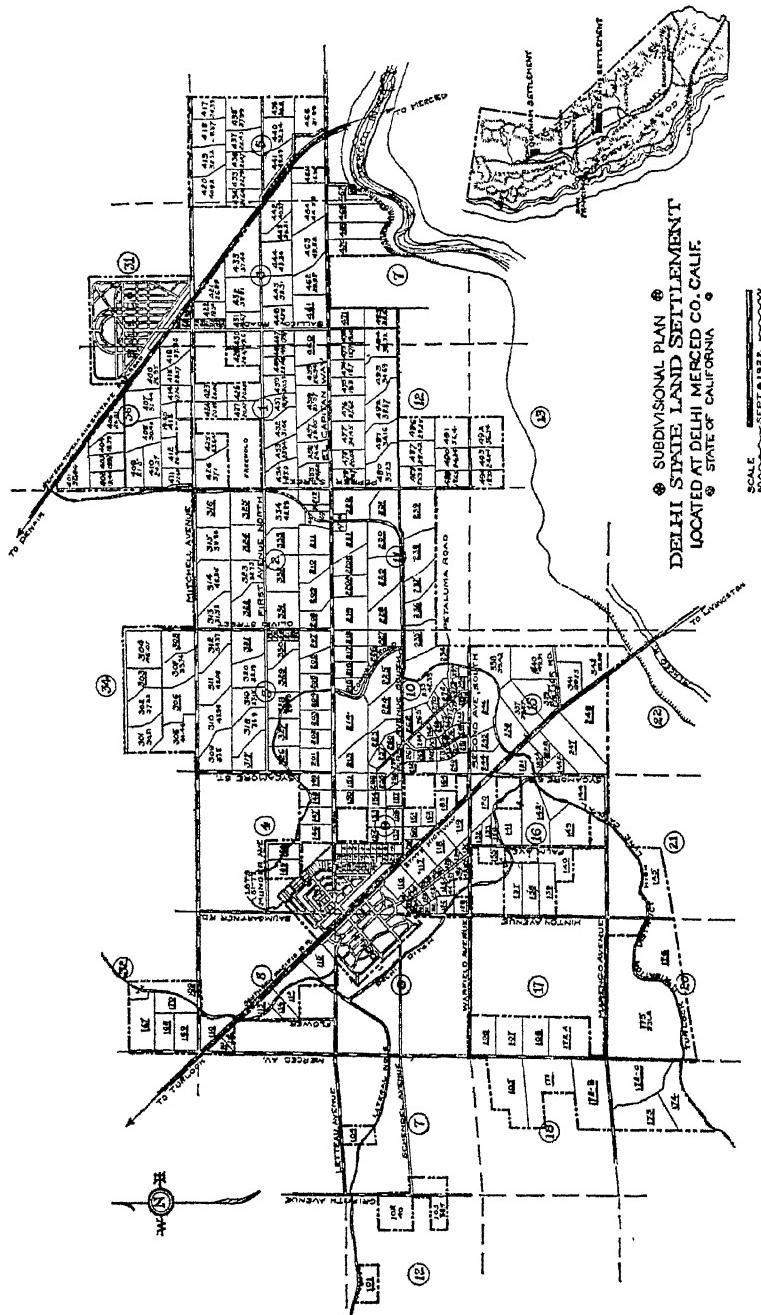


Fig. 3.—Copy of subdivisional plan, Delhi State Land Settlement, September, 1922.

acre. The estimated cost of \$29 per acre for the distribution system was quite accurate, for the actual cost was figured by the engineers at \$33 per acre. It is not known, however, just how the engineers allocated the overhead costs between the distribution system and the farm laterals.

The cost of leveling was far greater than expected. During the winter of 1921-22, the settlement officers made a survey which included an inventory of improvements made and also plans for further improvements.<sup>55</sup> The data must have been accurate because loans were made in accordance with them; but since the terminology used was inexact, there was ambiguity in meaning. Leveling in some instances meant a complete job with checking; in some instances it meant without checking; and in others only rough leveling. In some cases, the acreage included the entire farm, and since portions used for crops other than alfalfa would not require such careful leveling, the cost given is low. The range was from \$13 an acre to over \$75. The cost for most farms was from \$33 to \$45 with \$35 as a conservative average. An extreme case was that of a settler who was billed by the settlement office for \$120 for the leveling, seeding to alfalfa, and spring irrigating of 1 acre, although the estimate for the job was \$45.

With the pipe laterals costing \$54 an acre and with leveling for alfalfa costing \$35, the total cost was about \$90, or more than double the estimated \$40. Adding the distribution system at an average cost of \$33 gives a total average of over \$120 for bringing the water to the land and preparing for alfalfa as compared with the 1919 estimate of \$69.

The costs incurred constituted a heavy drain on the resources of the Board and were not anticipated. This was due to the fact that the Board did not know how extensive a pipe system would be necessary or how much leveling would be needed. The engineers in their 1918 and 1919 report (cited in footnote 53, p. 411) had recommended a detailed survey in order to obtain this information but the Board had not considered it necessary. As will be described in a later section (p. 440-42), price changes cannot be held responsible.

Other pertinent information concerning the cost of the irrigation system is as follows. The estimated cost for 24-inch pipe installed was \$1.00 per foot; the actual cost was \$1.925 in 1920-21 and \$1.774 in 1921-22.<sup>56</sup> That the cost of the distribution system did not increase proportionately may have been due to the fact that the size of pipe installed was considerably smaller than the estimate called for. On the other hand, the mileage of distribution pipe was considerably greater for about the same acreage. The only increased cost in basic items such as labor or materials was a very slight 3 or 4 per cent rise in cement prices. (See fig. 5, p. 441.) Other items were lower in price. Because of the large amount of pipe needed, and because of the wish to reduce costs and to provide pipe exactly suited to needs, the Board built a pipe factory. Mr. Brown, in his 1923 report, stated that the factory with equipment and special railway siding, cost \$41,017.19. He added that:

In order to get a comparison of commercial factory costs to our own factory costs, we

<sup>55</sup> Files of Giannini Foundation.

<sup>56</sup> California Department of Public Works, Division of Land Settlement. Report of the Division of Land Settlement, a subdivision of the Department of Public Works of the State of California, to accompany the first biennial report of that department, September 1, 1922. p. 59. 1922.

asked Mr. Fred Stanley, engineer for the California Associated Concrete Pipe Manufacturers, to give us the commercial rates. He complied with our request and we have worked out comparative costs.<sup>57</sup>

Mr. Brown's summary was as follows:

	Commercial cost	Factory cost
1920-21 . . . . .	\$160,526.00	\$101,272.00
1921-22 . . . . .	129,309.00	66,935.00
1922-23 . . . . .	126,627.00	73,361.00
Saving to Colony.....		\$174,894.00 on three years' business or about 4 times the cost of the factory. <sup>58</sup>

While this information indicates that economical methods were used in construction, other reports give a less satisfactory picture. Almost every settler seemed to have some grievance; it is difficult, however, to fix the importance of the items they objected to. Some of the pumps were evidently of the wrong size. One farm system and possibly more were laid out in such a way that the water could not be easily applied, and the lines were subsequently moved—an expensive operation. Some pipe is reported to have been exposed to frost before being entirely cured and was consequently weak. The charge was made that surge pipes were not installed at some points where subsequently found to be needed. In 1923 and 1924 some pipe was laid which was too small; this was not due to design but to inadequate funds. It must be emphasized that construction was never completed. In 1931 when the state turned the system over to the Turlock Irrigation District, the district required that the state install some larger pipe and make a few other changes. These changes cost about \$25,000. While these faults cannot be ignored, the writer has come to the conclusion that the system as a whole has been reasonably satisfactory.<sup>59</sup>

<sup>57</sup> Brown, L. N. [Report of engineers to California State Land Settlement Board relative to cost of irrigation system as of June 30, 1923.] March 26, 1924. (Typewritten; in files of L. N. Brown.)

<sup>58</sup> *Ibid.*

<sup>59</sup> The following statements about the irrigation system may be quoted:

"I have made a rather careful analysis of the proposed concrete pipe distributing system for the first unit of the Delhi Colony.

"This analysis shows that with a reasonable allowance made in the quantity of water to be used when the project is fully under irrigation, the carrying capacities of the various lines are sufficient to meet all reasonable requirements." (Beckett, S. H., Associate Professor of Irrigation Practice, University of California. Quoted in: California State Land Settlement Board. Report... September 30, 1920. *op. cit.* p. 30.)

"In some cases at end of piping, limits of money forced use of smaller pipe than needed for full flow of water. This was due to financial needs, not to poor irrigation engineering." (Williams, Milo. Interview. March, 1935.)

"Theoretically the pipe system is superior to any other provided ample water can be supplied at all points, but in practice there have developed many disappointments along this line. The system was not thoroughly tested out until the dry season of 1924-25, when a considerable portion of the total acreage required irrigation. It thus developed that many of the pipe lines were of inadequate size, that there was a lack of proper gates and controls, and also deficiencies in mechanical and electrical appliances. Surge pipes were illly constructed and some have fallen with the wind. During the past two years much time and considerable money was necessarily expended in the effort to eliminate these deficiencies. Additional pipe lines have been laid; cross connections made, gates and control devices of a permanent type installed, automatic compensators and other electrical devices put in so that the system is now in practical and fairly economical operation." (Wooster, C. M., Chairman of the Board, 1924 to 1927. [Report to Governor F. W. Richardson.] December 31, 1926. Typewritten; in files of C. M. Wooster.)

"The water supply is among the very best in the entire state and during the recent dry season of 1924 no shortage of water was experienced in the colony. .... During 1924 a total

*Drainage.*—It was soon discovered that hardpan and the undulating topography prevented drainage and that in consequence the water table in the depression areas rose enough to kill the crops. To correct this the administration installed a number of drainage wells and pumps which, on the whole, were successful. Some crops, however, were lost, to the serious detriment of the settlers concerned. The Board also was put to heavy expenditure, though just how much is not known. The auditor in 1931 reported that a total of \$117,512.41 had been spent for "wells, pumping plants, etc."<sup>60</sup> While he listed engineering, surveys, pipe manufacture, pipe lines, pipe line repairs, and structures separately, he made no classification of the use of the wells and pumping plants. A number of the pumping plants were designed for lifting water from the river or canals, and a few wells were designed from the first not only for drainage but also to provide water when the Turlock District would not be supplying water in the winter time. Consequently, it has not been possible to separate these various uses. It is believed, however, that the larger part of this amount was spent in order to provide drainage.

The engineer who surveyed the tract for the drainage system made the following statement in his report:

Should this tract become irrigated and water was used as lavishly as it has been on many irrigation projects there will be a decided tendency to raise the water table and cause some of the depressions to become waterlogged.

Poor drainage, should it develop, from any cause will be limited to the depressions and it would probably be impossible to waterlog any considerable portion of the tract even with extravagant use of water....

Although it is a well-known fact that poor drainage often accompanies irrigation, it is usually difficult to foresee just how it is going to develop and a plan for drainage made before any indications for its need appear may either be inadequate or needlessly expensive.<sup>61</sup>

The author believes this is a fair statement of what could be learned about the tract. In any case no provision seems to have been made for the expenditures that were entailed. (See section on "Financing at Delhi," p. 451.)

*Poultry Farms.*—The poultry farms at Delhi had not been included in the original program. Two subsequent developments seem to have brought them

of 4615 acres was irrigated at an operation and maintenance cost of \$1.98 per acre." (Smith, J. Winter, Superintendent and Engineer at Delhi, 1924 to 1931. [Report to California Department of Agriculture, Division of Land Settlement. July 29, 1927.] Typewritten; in files of California Department of Finance, Division of State Lands.)

"There seems to be some question as to the adequacy of certain pipe lines and other works serving some of the units of the colony, and this condition should be either rectified before the District undertakes operation or provision made now for necessary expenditures to be made at the end of the first year's operation by the District." (Meikle, R. V., Chief Engineer, Turlock Irrigation District. Letter to J. Winter Smith relative to taking over of Delhi system by District. December 31, 1929. Files of State Land Settlement Office. Delhi, California.)

"It is estimated that an expenditure of \$25,000 will be necessary to put into shape the present system of pipe lines distributing water to land now under irrigation, amounting to approximately 5,000 acres, it is said.... This estimate was given by John D. Sillerman, former assistant engineer in the Colony." (Anonymous. Irrigation problems important in settlers' adjustment plans, opinion of Wednesday's meet. Delhi Record 6(49):1. January 10, 1930.)

<sup>60</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of August 13, 1931.] (Typewritten.)

<sup>61</sup> Weir, W. W., Drainage Engineer in the Experiment Station. [Report to California State Land Settlement Board relative to Wilson tract, October 31, 1917.] (Typewritten; in files of W. W. Weir.)

into the plan. For one thing, some applicants did not have the capital needed for buying a dairy or fruit farm and small poultry farms suggested a way of bringing these men into the settlement. At the same time one area had proved to have such poor soil that the chance of profitably raising crops on it seemed doubtful. Since the farms were already piped, steps had to be taken to realize on the investment. According to report, it was thought that the poultry farms could succeed regardless of the nature of the soil. By the summer of 1922 buildings had been erected that would shelter 30,000 hens.<sup>62</sup> Some veteran trainees were settled on these farms, and a special poultry instructor was brought in. The administration expected the area to be a poultry center and named roads serving it Petaluma Road and Feather Way.

*Townsites.*—The townsites of Delhi and Ballico had been plotted and recorded by former private settlement organizations but no development had ever taken place. The townsites were made up of 300 acres at Delhi and 200 acres at Ballico. At Delhi the Board drew up elaborate plans and spent considerable money in development. It was to be a model town built according to specifications drawn up by the University of California Division of Landscape Design. The Southern Pacific Railroad and the state highway crossed its center. On one side the residential district was to have a nucleus of a civic center, a main park and playgrounds, and the school grounds. Neighborhood park playgrounds were to be located in the center of many of the larger residential blocks. In the civic center the architecture was to be restricted to a mission-adobe style to insure uniformity and beauty. On the opposite side of the track provision was made for warehouses and manufacturing.

To start Delhi off, the Board immediately erected a number of buildings, and by November, 1920, the expenditures on the townsites totaled \$79,901. The chief items included an administration building (\$10,255) with a garage (\$993) and a well-and-pressure system (\$1,552.77); a pipe-yard shed (\$17,142); a warehouse (\$7,386); bunkhouses, barns, shops, and five staff houses. One staff house cost \$7,256; three cost over \$5,000 each; one was under construction; and a staff-house well-and-pressure system had been built for \$1,537. Considerable road grading and tree planting were done on the town-site.<sup>63</sup> Private interests, on the other hand, put very little money into the town. At Ballico, a school building and a few laborers' allotments were built.

Many settlers repeatedly questioned the desirability of some of these expenditures and were particularly resentful about the staff houses because they were so much better than the settlers' own houses. The construction may not have been necessary since Turlock was close by and was used as a place of residence by some of the staff. The Board assumed, however, that the town would grow and that there would be a need for such houses. An office and the buildings connected with the pipe factory were, of course, necessary. The book value given the townsites by the Board in 1924 was \$301,195, only a small portion of which was realized.<sup>64</sup>

<sup>62</sup> California Department of Public Works, Division of Land Settlement. Report... September 1, 1922. *op. cit.* p. 44. Later reports indicated that shelter for as many as 60,000 hens were located in the settlement.

<sup>63</sup> California State Land Settlement Board. Report... September 30, 1920. *op. cit.* p. 37.

<sup>64</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of December 31, 1924.] (Typewritten.)

### FARMSTEAD PLANNING AT THE SETTLEMENTS

One of the features of the state program was to have the engineers not only construct the irrigation system but also plan and, to a degree, develop each farm. Every effort seems to have been made to realize this objective. Farms and ditches were laid out so that no farm would be needlessly cut up. An engineer, Mr. Max Cook, was employed to supervise the building program of each settler. He worked first at Durham where his work was described as follows:

The plans of houses for settlers and their location on each farm were worked out by the farmstead engineer after he had gone into this matter fully with the settler and his wife. The plans . . . included the grouping of all the farm buildings and arrangement of roads, the garden, the orchard and fields of each farm. The settler began therefore with a working plan, not only for present, but future improvements. Nothing has been done in a casual or haphazard fashion and, as a result, a country neighborhood has been created in less than a year's time which, because of convenient arrangement of roads and farms and attractiveness of houses, is a source of pride and satisfaction to the settlers and presents a favorable contrast to the unplanned development of any new community elsewhere.<sup>65</sup>

Later at Delhi he was able to use many of his plans again and thus save on the expenses involved. The scope of his work there expanded steadily and in a press notice he described it in the following statement.

The activities of this department embrace not only planning, designing, quantity surveying, obtaining competitive bids, letting contracts, and supervising construction of all classes of farm, townsite, and administrative buildings, but include also making individual farmstead layouts for all settlers, determining location and arrangement of buildings, lanes, corrals, poultry runs, domestic wells, orchards, vegetable gardens, etc. Individual settlers are given unlimited consultation in acquainting them with state housing laws, dairy laws, sanitary rules, Board of Health recommendations relative to sewage disposal, protection of domestic water supply, insurance rates and hazards, requirements of good practice in plumbing, electric wiring, paint formulas, concrete mixing, chimney construction, carpentry, etc. All buildings are appraised and values set for basis of loans, and all buildings rented are scheduled by this Department.

Active interest and support is given to community development, services being extended to School Board and Settlers' Coöperative Association. This included preparing plans and supervision of construction of the Community Hall at Delhi which was recently completed.<sup>66</sup>

Most settlers, particularly those at Delhi, could not afford satisfactory houses and planned to build only part of the house or, temporarily, even to live in garages or henhouses. The former device was common and plans were carefully drawn so as to permit later enlargement. That costs were kept down is evidenced by data which give the final average building development at Delhi per farm as \$1,701, per poultry allotment as \$1,405, and per laborers' allotment as \$903. (See table 2, p. 432.) There was, however, some waste at Durham where a number of buildings, such as barns and silos, were built and later left unused because the owner, either voluntarily or because of crop failures, shifted from one enterprise to another.

Although usually coöperative, each settler had his own wishes, which the engineers could not always gratify. When the officials acted, through their control over credit, to prevent what they thought were wasteful expenditures,

<sup>65</sup> California State Land Settlement Board. Information regarding progress . . . May 30, 1919. *op. cit.* p. 15.

<sup>66</sup> Anonymous. Progress report on building settlers' homes in the California State settlement at Delhi. Press notice. (Mimeograph; in files of Giannini Foundation.)

they sometimes aroused ill feeling. If the settlers' expectations of more comfortable homes in the future had been realized, this early ill feeling would doubtless have been forgotten. As it was, however, the settlers were left with some very poor houses and they were bitterly resentful.

### THE SETTLERS

*Selection of Settlers.*—The Board planned to select settlers on their ability to succeed and to fulfill the objectives in mind. This program was possible to some extent at Durham. As there were at first more than one applicant for most farms, the Board could discriminate and still sell the land. But the surplus of applicants did not last long. Moreover, it is sometimes claimed that even where selection was possible, the results in a few cases were not what had been hoped for; the administration was influenced more by the personality of the applicant than by his abilities. Some of the settlers seem to have been attracted more by the reform elements of the program than by the opportunity to buy and develop a farm.<sup>67</sup> In general, however, most of the settlers at Durham were apparently of a type that any community would consider desirable.

The same program for selection was planned for Delhi but was never possible of fulfillment. Since there was from the first a lack of settlers, everyone who satisfied the minimum requirements was accepted. A curiously diverse group, in fact, were admitted to the Delhi tract.<sup>68</sup> It was later learned from the records that 38 per cent of the settlers had come directly from farms, that 23 per cent had been reared on farms, that 27 per cent had farmed for over twenty years, and that 8 per cent had had no farming experience.<sup>69</sup> Only a few had lived on irrigated farms. Many listed themselves as laborers. While a large number of the Delhi settlers were inexperienced and some were unfit, the majority appear to have had the fundamental requisites of desirable settlers.

Veterans were always numerous at Delhi, at one time making up about one half of the settlers.<sup>70</sup> In fact, the law required that ex-service men be given preference; but this never excluded other people, since there were never enough applicants to take care of the available allotments.<sup>71</sup> The United States Veterans Bureau soon placed 12 of their trainees in the settlement, and later as many as 23 are reported to have been located there.<sup>72</sup> Each man received

<sup>67</sup> Supporting information is confidential.

<sup>68</sup> The Division of Land Settlement in 1922 stated that some of the settlers in their applications had listed themselves as follows: storekeeper, civil engineer, auto mechanic, traveling salesman, sign painter, plasterer, bookkeeper, telegrapher, carpenter, photographer, hand-coloring photographer, African guide and big-game hunter, band leader, minister, orchestra player, florist, radio operator, movie-machine operator, shipbuilder, and sailor. There were teachers of high school, grades, kindergarten, piano, stringed instruments, elocution, and aesthetic dancing. There were a real-estate salesman, a land appraiser from the Federal Land Bank, an irrigation engineer, and a farm advisor. There were a milliner, a dressmaker, a rug weaver, a street-car conductor, a railway locomotive engineer, an electrician, an electrical engineer, an automobile salesman, a cheesemaker, a banker, a gardener, a fireman, an osteopath, a physician, a trained nurse, a baker, a house painter, a shoemaker, a stenographer, a plumber, a policeman, and an aviator. (California Department of Public Works, Division of Land Settlement. Report . . . September 1, 1922. *op. cit.* p. 40.)

<sup>69</sup> Smith, J. Winter. (*Files of State Land Settlement Office, Delhi, California.*)

<sup>70</sup> California Department of Public Works, Division of Land Settlement. Report . . . September 1, 1922. *op. cit.* p. 40.

<sup>71</sup> California Statutes, 1919. Chap. 450, See. 15.

<sup>72</sup> California Department of Public Works, Division of Land Settlement. Report . . . September 1, 1922. *op. cit.* p. 47.

vocational training and from \$95 to \$155 monthly plus an initial \$300 for equipment.

*Early Attitude.*—Few items concerning the history of the settlements are more often insisted upon by people acquainted with the settlers than that during the first years the settlers, as a whole, were very coöperative and enthusiastic. Mr. R. V. Wright, a member of the Agricultural Extension Service of the University of California, who did a great deal of work on the settlement at Durham, reported as follows:

The spirit of coöperation that prevails at the Durham State Land Settlement Colony is the thing that impresses a person most forcibly when visiting the colony.

Community production and coöperative marketing are considered as vital points in the success of the settlers. Along with the development of the phases that affect the economic side of the colony, the settlers are also developing a wonderful spirit of fellowship that shows up in the community park and meeting place. The aim of the settlers is to create a social and civic condition in the country equal to that of the city, realizing that economical success depends to a greater or less extent upon the morale of the settlers and their families.<sup>73</sup>

The Board itself reported the situation as being as follows:

In the earlier pages of this report, the superintendents of the Durham and Delhi colonies have told of the coöperative activities of the settlers and of the fine results which have followed. . . . All are agreed that the finest feature of these settlements is the enthusiasm and civic pride of the people.<sup>74</sup>

*Community Activities.*—This spirit was shown particularly well in the coöperative and social activities established at the settlements. These activities, of course, had been a part of the original plan which was that settlement should be by groups and not by individuals, but coöperation in business and social life would never have attained the importance it had for a time if the settlers had not given it their wholehearted support. Purchasing and selling coöperatives were organized at both settlements. At Durham, particularly, a milk-selling association and a cold-storage association formed the hub of the dairy industry.<sup>75</sup> Purebred sires were purchased and managed on a community basis. Arrangements were made for a veterinarian to live at Durham, and owners contracted with him to have their herds cared for at a fixed annual sum.<sup>76</sup> This coöperative spirit was exemplified in an early purchase of dairy cows by the settlement committee charged with that duty. After the purchase the tuberculin test revealed that nearly a carload were reactors. Although individuals had legal title and stood to take the loss, the community voluntarily contributed half the purchase price to the parties directly concerned.<sup>77</sup>

Unfortunately, however, at both settlements most of the coöperative attempts were unsuccessful. Criticism and disputes were common. According to the superintendent of the Delhi settlement, who had made every effort to encourage coöperative buying:

The attempt . . . was made in order to prove whether or not this sort of activity could be carried on with any saving to the colony. The bad outcome led to a discontinuance of this work.<sup>78</sup>

<sup>73</sup> California State Land Settlement Board. Report . . . September 30, 1920. *op. cit.* p. 18.

<sup>74</sup> *Ibid.* p. 46. <sup>75</sup> *Ibid.* p. 14. <sup>76</sup> *Ibid.* p. 17.

<sup>77</sup> Mead. Helping men own farms. *op. cit.* p. 144.

<sup>78</sup> Packard, Walter E. [Report on the Delhi State Land Settlement as of February 1, 1924, to C. M. Wooster, February 8, 1924.] (Typewritten; in files of California Department of Finance, Division of State Lands.)

A similar endeavor was made with social activities. Community halls were built at both places. Fairs were held to advertise the tracts and to encourage competition among the settlers. Organizations for many purposes were developed. But like the co-operatives most of these activities soon disappeared.

*Early Dissatisfaction.*—From the very first there were, of course, a few settlers who caused trouble. Some were totally inexperienced in farming and some anticipated that state aid and direction assured them of successful development regardless of effort. Some were unwilling or unable to make the effort necessary to establish themselves.<sup>70</sup> The administration seems to have made every effort to encourage and aid these people. The only criticism that might be made is in regard to leniency. Some settlers were left on their allotments although it now appears clear that they had little prospect of success. The need for keeping land under contract, the political difficulties of foreclosure, and an earnest desire to help, explained the administration's delay and liberality.

The following data show the approximate number of allotments owned and occupied at Delhi by one, two, or more settlers during the period considered, that is, 1920 to 1930. One hundred and fifteen allotments had had only one settler owner each during the period; 155 allotments had had two each; 51 allotments had had three each; 11 allotments had had four each; 2 allotments had had five each; and 1 allotment had had eight different settlers during the period. Of these, 52 were laborers' allotments—that is, tracts of less than 3 acres. Of the laborers' allotments, 12 had had one owner; 23, two; 13, three; 3, four; and 1, eight. Evidently the laborers' allotments changed hands much more frequently than the other tracts. Most of these changes occurred during the early years.<sup>71</sup> While it is not known whether this movement was exceptional in such projects, it does appear to be indicative of some discontent.

<sup>70</sup> For example, one woman with evidently no farm experience was accepted only because settlers were needed and because she insisted despite Mr. Packard's advice. Placed on a partially developed allotment with some berries planted on it, she made no move to care for them until they very much needed attention. Then she called at the office and asked when they were going to send some one over to do the work. As another example, a couple, while being taken out to their allotment, enthusiastically told of a correspondence course that the husband had taken on farming and passed with a mark of one hundred. Among other things he described what he had learned about raising alfalfa. When they arrived at the farm, he looked around and wanted to know what was growing in an adjacent field. It was alfalfa. (Packard, Walter E., Superintendent. Delhi State Land Settlement.)

Another settler abandoned his allotment twice within two years but was allowed to return each time under a special agreement, which he immediately repudiated. He neglected his trees so that the settlement officials had to arrange for their irrigation. The Division of Land Settlement paid the Horticultural Commission \$200 for destroying weeds that he permitted to grow. During the three years he held the place he made no payments. An arbitration committee was appointed with his approval; but he refused to accept its decision. As he was a veteran, the Vocational Board gave him a training allowance; but they had to withdraw it. When the Board officials threatened foreclosure he obtained delay by appealing to the Governor. Not until the third year did the state really start proceedings, and even then it did not carry them out. At that time his accumulated delinquencies had mounted to more than his equity, but the state paid him \$800 to sign a quitclaim deed and turn over the property. (Files of State Land Settlement Office, Delhi, California.)

Another settler had become discouraged by 1922 and when asked to take out a Federal Land Bank loan, he acquiesced only on condition that the state loan him funds for further improvements. He was already delinquent when the Federal loan was made and failed to make any payments during the next few years. Foreclosure was started but never carried through. (Files of State Land Settlement Office, Delhi, California.)

<sup>70</sup> Original data obtained from files of State Land Settlement Office, Delhi, California.

Although no comparable data are available at Durham, a somewhat similar situation prevailed. On February 15, 1921, the Division of Land Settlement advertised 7 farms and 3 farm laborers' allotments for sale.<sup>51</sup> In September of the same year another listing was offered but only 1 allotment listed in the advertisements of February was listed in September, though 12 were offered.<sup>52</sup>

No record is available of the number of settlers who left the settlements, but reports indicate that it must have been large, particularly of those on laborers' allotments. The laborers who came worked at first on construction, but with its end they found little else to do and many soon left. Since there were few opportunities for work among the settlement farmers—they themselves were frequently looking for work—very few agricultural laborers purchased the small allotments, although they occasionally rented them for a season. At both settlements a large proportion of those who purchased and stayed on the small allotments had pensions or similar incomes, or had jobs in near-by towns or in other areas. These people were attracted by the inexpensive homes.

#### SELLING THE LAND

The California State Land Settlement Board seems to have anticipated no difficulty in selling its land, and in the initial offering at Durham it had a large number of buyers. All the laborers' allotments and all but 4 of the farms were sold.<sup>53</sup> However, while sales were frequent, there were always a few farms for sale, some by the state and some by settlers.

At Delhi, the administration found selling to be difficult from the first. The land was first available for sale on April 27, 1920, but by September 30 there were still 30 farms and 11 laborers' allotments for sale out of the 97 farms and 58 laborers' allotments offered.<sup>54</sup> Unfortunately, sales became progressively slower and often were at a complete standstill. Because of the need to sell, a strong selling organization with widespread connections was soon built up.

The Board had hoped that little expense would be incurred in selling the land and described its work up to September of 1922 as follows:

The only expenses have been the legal advertising which the law requires, the printing and mailing of circulars of information, and the expenses of a man and automobile to show land seekers over the property. In all it does not amount to one per cent of the selling price of farms.<sup>55</sup>

It is impossible to check the actual cost of selling the land because many expense items could be charged either to sales or to other phases of the work. It appears, though, that a number of the staff members gave a great deal of their time to selling and that if their work had been charged differently, the reported cost of selling would have been greater. All local expenses, however, were minor in comparison to the aid given by other organizations in advertising the settlements.

<sup>51</sup> California State Land Settlement Board. Durham. State land settlement farms. February 15, 1921. (Broadsides; in files of Giannini Foundation.)

<sup>52</sup> California Department of Public Works, Division of Land Settlement. History of the Durham state land settlements, table and description of available allotments at Durham. September, 1921. (Broadsides; in files of Giannini Foundation.)

<sup>53</sup> California State Land Settlement Board. Report... June 30, 1918. *op. cit.* p. 11.

<sup>54</sup> California State Land Settlement Board. Report... September 30, 1920. *op. cit.* p. 35.

<sup>55</sup> California Department of Public Works, Division of Land Settlement. Report... September 1, 1922. *op. cit.* p. 16.

Dr. Mead had a wide acquaintance and was able to obtain a great deal of publicity for the settlements. Magazines and newspapers of every type carried articles or news items by Dr. Mead, by other officials, or by special feature writers. By an extensive correspondence Dr. Mead kept up editors' interest. The California Development Association and Californians Inc., both semi-public advertising agencies, included Durham and Delhi in their publicity for the state.<sup>56</sup> The California Agricultural Experiment Station published two circulars on rural development and colonization.<sup>57</sup> The Santa Fe and the Southern Pacific railroads gave a great deal of help. In one mailing the Santa Fe sent letters to 30,000 selected farmers in the Middle West.<sup>58</sup> This advertising aroused tremendous interest and the Division of Land Settlement received upward of 10,000 inquiries in 1921.<sup>59</sup> Besides obtaining this advertising, the administration did all it could to make the colony attractive; for instance, prizes were offered for the best-kept gardens. The Southern Pacific built an attractive station at Delhi, and the Santa Fe was asked to build one at Ballico.<sup>60</sup>

Nevertheless, the land did not sell. When the third unit was opened, almost the entire north end was left unsettled. In the fall of 1922, with the fourth, or Ballico unit, to be opened, extra effort was put into selling. Seventy-five veteran trainees from Rough and Ready Island, an agricultural training center of the Veterans Bureau, were shown the land.<sup>61</sup> Fifteen thousand copies of the introduction to a biennial report were distributed.<sup>62</sup> A special land office was opened at Ballico with an assistant superintendent in charge. A widely advertised fair demonstrated the progress and spirit of the community; 2,000 people were fed at one sitting. The failure of the campaign, however, was abrupt and disheartening. When the new allotments were opened hardly an applicant came. In a few days the Ballico office was closed. Even inquiries ceased. There were 34 farms and 3 laborers' allotments for sale in the older units,<sup>63</sup> 97 farms and 8 laborers' allotments in the Ballico unit.<sup>64</sup> Out of these only 21 applications for farms and 6 applications for laborers' allotments were accepted that fall. Only a part of these applicants became settlers.<sup>65</sup>

<sup>56</sup> Files of Giannini Foundation.

<sup>57</sup> Mead, How California is helping people own farms and rural homes. *op. cit.*

Mead, Elwood, C. F. Shaw, R. L. Adams, and J. W. Gregg, Colonization and rural development in California. California Agr. Exp. Sta. Cir. 247:1-72, 1922. (Out of print.)

<sup>58</sup> Seagraves, C. L., General Colonization Agent, The Atchison, Topeka and Santa Fe Railway Company. Letter to Elwood Mead. October 27, 1922. (Files of Giannini Foundation.)

<sup>59</sup> California State Land Settlement Board. Report .... September 30, 1920. *op. cit.* p. 16.

<sup>60</sup> Mead, Elwood. Letter to J. W. Walker, Superintendent, The Atchison, Topeka and Santa Fe Railway Company, Fresno, California. August 23, 1922. (Files of Giannini Foundation.)

<sup>61</sup> Mead, Elwood. Letter to A. B. Fletcher, Director of Public Works, Sacramento, California. August 10, 1922. (Files of Giannini Foundation.)

<sup>62</sup> Fletcher, A. B. Letter to Elwood Mead. September 14, 1922. (Files of Giannini Foundation.)

<sup>63</sup> California Department of Public Works, Division of Land Settlement. Allotments in the Delhi State Land Settlement which are available, September 15th, 1922. (Typewritten; in files of Giannini Foundation.)

<sup>64</sup> California Department of Public Works, Division of Land Settlement. Information for intending settlers regarding the Ballico unit of the Delhi Settlement. September, 1922. (Broadside; in files of Giannini Foundation.)

<sup>65</sup> Anonymous. [Description of sales made at Delhi.] Press letter. (Files of Giannini Foundation.)

California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of December 31, 1922.] (Typewritten.)

The administration, however, immediately mapped out another campaign. The Board of Control voted \$1,000 to finance necessary expenses, Mr. Kreutzer visited the Middle West to talk with interested people, and the two railroads and Californians Inc. advertised the trip. But he brought back only four or five applications.<sup>70</sup> In this campaign they gave a great deal of attention to southern California and obtained help from local papers, county farm advisors, and farm bureaus. Both Mr. Packard and Mr. Kreutzer made special trips to Los Angeles and the surrounding area. Finally, the advertised capital requirement for farm allotments was lowered from \$2,500 to \$1,500. Still they could not sell the land; virtually no sales were made during 1923. Mr. Packard's final report in February, 1924, stressed the importance of sales as follows:

The most important consideration is the sale of farms, both to permit those to sell who wish to leave and to replenish the state funds. There are approximately thirty-two partially developed farms for sale in the settlement. If these could be sold, it would return to the Land Settlement Board approximately \$26,000 in deferred payments to the state. There are 35 farms that are piped but not sold which, if sold, would return approximately \$15,000 to the state.<sup>71</sup>

The 32 partially developed farms Mr. Packard refers to were farms which settlers had left or wanted to leave. The 35 farms were those on which the state had placed some improvements. There were other large acreages waiting improvement. The total acreage unsold on December 31, 1924, amounted to 3,528 acres. It had a book value of \$933,527.36.<sup>72</sup>

This inability to sell land was not due to lack of publicity, sales effort, or expense. The reasons for there being unsold land will be given in the discussions on "Production Problems" and "The Economic Situation."

## PRODUCTION PROBLEMS

### DURHAM PRODUCTION PROBLEMS

*Adobe Lands.*—During the first years at Durham the only major production problem was with the adobe soil, which lay over a considerable portion of the southern section of the tract and which had been valued at \$40 to \$50 an acre.<sup>73</sup> (See soil map, fig. 1, p. 408.) The nature of this soil had been reported to the California State Land Settlement Board as follows:

The Vina clay adobe . . . will do well with grain, corn, rice and similar crops. Alfalfa could be grown but the slow penetration of water would make irrigation very difficult. Their heavy nature and tendency to become sticky when wet would make them difficult to handle. At the

<sup>70</sup> Mead, Elwood. Letter to Chas. S. Fee, Southern Pacific Company, San Francisco, California, February 14, 1923. (Files of Giannini Foundation.)

<sup>71</sup> Packard, Walter E. [Report . . . February 8, 1924.] *op. cit.*

<sup>72</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of December 31, 1924.] (Typewritten.)

<sup>73</sup> Kreutzer, Geo. C. Valuation and report on the Lott Estate to State Land Settlement Board, May 4, 1918. (Typewritten; in files of California Department of Finance, Division of State Lands.)

Kreutzer, Geo. C. Letter to Elwood Mead, January 15, 1918. [Report on investigation of Stanford, James, and Wilson tracts.] (Files of California Department of Finance, Division of State Lands.)

Stimmel, W. G. [Memorandum on prices of land owned by Stanford University and Charles F. Lott offered for sale to California State Land Settlement Board by W. G. Stimmel.] (Typewritten; in files of California Department of Finance, Division of State Lands.)

present time most of these . . . soils are being used for pasture or grain, though there is a large field of rice.<sup>100</sup>

In the past, this area had not been farmed every year. Little irrigation had been tried except with rice which required large quantities of water. Although summer-fallowed, the grain crops were susceptible to drought. There is evidence that the Board and the settlers had more hopes about this soil than either the soil reports or the experience of local farmers justified. Alfalfa was tried again and again, as many as four times, but it always proved a failure. These attempts were particularly frequent on soils close by and related to the clay adobe. The report of the Superintendent regarding the adobe farms was as follows:

. . . due to two years' grain failure and the necessity of summer fallowing every other year, the lands in so small an acreage did not seem to work into suitable farms. Had the farmer developed his area to livestock instead of to grain alone we believe his chances of success would have been considerably greater, but this was not done for various reasons. The larger areas seemed to be too great a burden to continue to carry so the State Land Settlement Board arranged with the settler to take back his adobe portion and allow him to keep the loam block, in order that he could go on and improve a farm and home for himself instead of being a failure.<sup>101</sup>

Financially, the farmers on the adobe soil were never able to make progress. The settlement farms, though similar in size to many in that area, were much smaller than those where barley and rice were grown. To work this adobe land, heavy and expensive equipment was needed which could never be made to pay except on farms several times as large as those the settlers had. There were great risks in such enterprises; the settlers with their small resources and heavy debts needed a more certain and regular income. Consequently the Board arranged to take back the adobe blocks. The details of these transactions are not available, but the Board, in order to reimburse the settlers for their equity, is reported to have credited the settlers with an equal amount on the land they retained.

*Later Production Problems at Durham.*—During these same first years the production programs of the farmers on about 3,600 acres of the better soils seemed to be going ahead without general difficulty. At times there were some 1,500 acres of alfalfa and, by 1925, over 500 acres with orchard crops, mostly prunes, on these soils.<sup>102</sup> The alfalfa was the most important crop in the settlement and on it depended the dairy enterprises in which most of the settlers were interested. While a number of individuals had serious difficulty from the start, until 1924 there seem to have been no widespread losses. From then on, however, very few farmers were able to obtain a satisfactory crop of either

<sup>100</sup> Shaw, C. F. [Report to California State Land Settlement Board, December 1, 1917, relative to Durham soils.] (Typewritten; in files of California Department of Finance, Division of State Lands.)

<sup>101</sup> Marshall, Margaret, Superintendent. Letter to C. M. Wooster. January 14, 1926. (Files of California Department of Finance, Division of State Lands.)

<sup>102</sup> California Department of Public Works, Division of Land Settlement. Report . . . September 1, 1922. *op. cit.* p. 20.

Basic data used through courtesy of the U. S. Bureau of the Census for: Teele, R. P., and Paul A. Ewing. The economic limits of cost of water for irrigation, the Durham State Land Settlement, California. A preliminary report, p. 1-80. U. S. Dept. Agr. Bur. Agr. Econ. and Bur. Pub. Roads. 1925. (Mimeo.)

Supplementary information from field investigation.

prunes or alfalfa. The appraisal made in 1929 revealed that less than a quarter of the farmers had alfalfa, and of these, many had very poor crops. The report listed some 30 orchards, but in almost every case they added little value to the farm and were described as poor.<sup>103</sup> These losses were important, for census data of 1924 show that the enterprises which were later adversely affected were the source that year of \$142,061, or 77 per cent of the receipts from all enterprises.<sup>104</sup>

The most profitable type of farming left was double cropping with grain and beans, a practice now usual and fairly profitable. The deep-rooted crops were not completely eliminated; they were still grown by a few farmers more fortunately situated and were repeatedly planted by others. Some of the dairy enterprises survived, but often by the use of roughage feeds other than alfalfa. These feeds, however, required a much larger acreage per cow and hence produced a lower return per acre.

These changes seriously affected the settlers and the state. For the settlers to make a living with low-income crops much larger farms were required than had been provided. The land had been priced with the expectation that alfalfa and fruit could be grown; land suitable only for grain and beans was worth much less. Heavy investments had been made in crops and equipment which were no longer productive. In fact some settlers had shifted from dairying to fruit and were indebted for both enterprises when they were forced to turn to a third and much less intensive type of farming. Mr. R. V. Wright, an appraiser and specialist in farm management, described the situation as follows:

Regarding the size of farm units, I believe that unless many of the farms are united, there will not be a very stable and satisfactory economic situation in the colony, even with the best of a drainage and irrigation system.

In my opinion there should be no farms with less than forty acres, and with the heavier soils a much larger farm is needed. The investment in buildings and equipment is prohibitive on the small places, and without satisfactory buildings and equipment good farm management can not be practiced.<sup>105</sup>

There is no reason to believe that the administration expected the settlers ever to be dependent on low-income crops. The proponents of the program were well aware that the area of land necessary to obtain a given income depends in considerable part upon the crop raised. For instance, Professor Thomas Forsyth Hunt, Dean of the College of Agriculture, pointed out in 1914 that the area needed to obtain a gross income of \$4,000 varied from 20 acres with oranges, to 40 acres with potatoes, to 60 acres with alfalfa and a dairy, and to 200 acres with barley.<sup>106</sup>

<sup>103</sup> Wright, R. V., Appraiser. [Report to California State Land Settlement Board.] February 27, 1929. (Typewritten; in files of California Department of Finance, Division of State Lands.)

<sup>104</sup> Teele, R. P., and Paul A. Ewing. The economic limits of cost of water for irrigation, the Durham State Land Settlement, California. A preliminary report. p. 1-30. U.S. Dept. Agr. Bur. Agr. Econ. and Bur. Pub. Roads. 1925. (Mimeo.)

<sup>105</sup> Wright, R. V. Letter to C. W. Cleary, Chief of the Division of Land Settlement, February 27, 1929. (Files of California Department of Finance, Division of State Lands.)

<sup>106</sup> Hunt, Thomas Forsyth, and other members of the staff. Some things the prospective settlers should know. *op. cit.* p. 1-63.

Also see California Commission on Land Colonization and Rural Credits. Report.... *op. cit.* p. 79.

*Causes of Crop Failures.*—It is evident that the losses of alfalfa and prunes were the most serious events on the settlement. The question then arises of why the crops were lost and whether or not these might have been foreseen and prevented. Dieback is often assigned as the cause for losses in prune trees. The following statement summarizes the results of extensive studies of the problem by the California Agricultural Experiment Station.

In 1921 the attention of the California Agricultural Experiment Station was called to a development of scourge of the foliage (dieback) of Agen prune trees in the upper Sacramento Valley. The area affected became larger as new orchards came into bearing, and now the trouble seriously threatens some 15,000 acres of trees located in Butte, Tehama, and Glenn Counties. Detailed studies in the field and in the laboratories of the plant nutrition and pomology divisions have been carried on since 1926 and it is fairly well established that faulty potassium nutrition of these prune trees is an important factor in the development of the trouble.<sup>107</sup>

The same faulty potassium nutrition has been observed in alfalfa. Other diseases are also common with this crop.

Another major difficulty with both crops was poor drainage. Almost the entire area of good soil was subject to flood and to a high water table. The water table, moreover, was fluctuating. While shallow-rooted crops were occasionally flooded out, deep-rooted crops were seriously damaged. Poor drainage has always been emphasized by the settlers as a cause for their losses because deep-rooted crops were the ones that died. The following paragraphs by different authorities describe the situation:

This land has apparently filled up with water which can not now get away. . . . A considerable part of the area is going into the winter with a water table within 6 or 8 feet of the surface, in some places nearer, and this means that 15 or 20 inches of rain is all that will be necessary to completely saturate the land.<sup>108</sup>

The general drainage conditions at Durham, I find to be very much more serious than anticipated. The majority of the acreage has the water table at such height as to be a menace to vegetation and in many cases absolutely prohibitive to fruit trees, the depth to ground water varying from 2 feet to 7 feet in all places where data were available. The soils vary considerably throughout the colony, most of them however, being very heavy, which fact greatly retards percolation of water and makes proper drainage a very difficult process. The open ditch system, so far as developed at present, is rather unsatisfactory due to the fact that the slow percolation thru the soil limits the effectiveness of any drain to a narrow strip of land adjoining.<sup>109</sup>

The Durham State Land Settlement . . . is badly waterlogged.

Prior to 1918 only a small portion of the land which now constitutes the State Land Settlement at Durham had been graded and very little of it was irrigated. The land was used chiefly for grain raising, and was in very near its natural condition as to topography and irrigation. The land was crossed by many sloughs and gullies and there is no record of any need for drainage, all excess water being carried off by natural drains. There are reports of severe floods at various times in intervals of several years but these floods were of very short duration and the land soon drained off showing no ill effect from the excess water. After the land

<sup>107</sup> Lilleland, Omund. Experiments in K and P deficiencies with fruit trees in the field. Amer. Soc. Hort. Sci. 1932 Proc. 29:272. 1933.

<sup>108</sup> Weir, W. W., Drainage Engineer in the Experiment Station. Letter to Mrs. Margaret McRae, Superintendent at Durham, November 24, 1926. (Files of California Department of Finance, Division of State Lands.)

<sup>109</sup> Smith, J. Winter, Engineer and Superintendent at Delhi. Letter to C. M. Wooster, Chairman of the Board, March 10, 1927. (Files of California Department of Finance, Division of State Lands.)

had been subdivided and the settlers came onto the ground, things were decidedly changed; all of the farms were graded so as to facilitate irrigating. The natural drainage courses were filled in if they happened to cut through the middle of a man's farm and no channels were excavated to take their place. An irrigation system was also installed. In laying out this project no regard was given the natural drainage, where it was necessary for the irrigation canals to cross a slough or small gulch the drain was filled in and the canal built across it. In some cases check gates were built across the natural drainage channels such as Robber's Gulch and these channels were converted into irrigation canals. In other cases irrigation canals were built so deep as to be almost adequate for drainage canals, but in these deep canals headgates were placed and during certain seasons of the year water was headed up in these canals to considerable heights. The canals which might have served to drain the land were now forcing water back into the land and causing it to become waterlogged.

After complete settlement of the Colony the land had all been leveled and was so graded that the only existing natural drains, of the many original ones, were Hamlin Slough, Robber's Gulch, and the lower end of Turtle Slough..... Of these drains, Hamlin is on the eastern extremity and drains only the pasture land and the heavy adobe soils. Robber's Gulch was obstructed by numerous headgate structures and converted into an irrigation canal and the remaining part of Turtle Slough was crossed by two or three bridges or culverts wholly inadequate to allow the passing of the winter flow in this channel. This slough was also allowed to become overgrown with weeds, thus greatly reducing its capacity.

Doubtless the poor farming conditions due to lack of drainage in the Durham Colony would be greatly lessened if the natural drainage channels had been left unmolested or if they were to be reopened.<sup>110</sup>

Regarding the drainage and irrigation situation, I have assumed that it will be necessary to line several irrigation ditches with concrete and deepen some of the existing drain channels and build additional drain ditches. The cost of such improvements would in my judgement not exceed \$50 per acre. This would provide an adequate irrigation and drainage system for the entire colony. If and when such a system is established, the land values would automatically rise \$50 per acre. Hence I have depreciated the land values approximately \$50 per acre due to the lack of such a system at this time.<sup>111</sup>

It should be noted that in places the bed of Butte Creek was above the level of the surrounding land and consequently did not provide direct drainage from the settlement. The sloughs that drained the land led through the tract and joined the creek farther down. In early days Butte Creek had often overflowed its banks and had completely changed its course several times, but levees were built along the creek and this overflow was prevented. The chief flood difficulties afterward came from storm waters from surrounding territory that drained onto the settlement land. When floods occurred, Butte Creek would also be filled, and the water could not escape rapidly.

The engineers in general agreed that the excess water was caused by waste in the application of irrigation water to the land, by seepage losses from irrigation ditches and Butte Creek, by obstruction of natural drainage ways, and by saturation of the soil with rainfall during the winter months. One man mentioned that the extensive growing of rice in the region to the south retarded the lateral movement of underground water. There was no unanimity, however, in the solutions proposed. They ranged from very expensive tile drainage to relatively simple ditching. One scheme would have cost \$200,000, or \$60 an acre, on the better soils. It is not known, of course, whether any method would

<sup>110</sup> Baxter, W. S. A report on the drainage of the Durham State Land Settlement. (A type-written thesis prepared at the University of California College of Civil Engineering, May, 1929.)

<sup>111</sup> Wright, R. V. Letter to C. W. Cleary, February 27, 1929. (Files of California Department of Finance, Division of State Lands.)

have been successful, at least from an economic viewpoint. Nothing that might have been adequate was attempted. When money was available the officers lined irrigation ditches where seepage was particularly bad and installed or improved drainage tile and ditches.

Mr. Wright, who made the 1929 appraisal for the state, described the situation as follows:

Regarding the crop adaptability of the better soils on the colony, I have considered that the following crops may be grown successfully: alfalfa, beans, corn, sudan, wheat, barley, oats and other general farm crops common to this part of the state. Fruit crops may do well under certain conditions and in a few places but as a general thing for the colony, I would say that fruit crops are very doubtful and too speculative for the settlers to deal with. The difficulty that many of the settlers have had in reseeding alfalfa is very puzzling. It is a known fact that alfalfa has been grown successfully on the colony for a long period of years, even before the colony was established. I firmly believe that with the proper soil management and drainage that alfalfa may again be successfully and generally grown in the colony. Perhaps some of the essential plant foods have become locked up, so that they are not readily available for the roots, if so it will require some treatment that will liberate these elements.<sup>112</sup>

Whether dieback or poor drainage was more important was immaterial from the standpoint of the success of the settlements. It seems likely that if either could have been corrected, the other would have prevented any very marked improvement.<sup>113</sup>

On the other hand, when consideration is given to the possibility of correction and particularly to the possibility of anticipating the difficulties, the two problems are very different. Dieback was not known at the time the Durham land was purchased, and there was no reason for anticipating it. The same statement cannot be made concerning poor drainage. The official report made to the Board before the land was purchased contained recommendations that some work be done to provide outlet drains for these floods. The statement, in part, was as follows:

Inquiries regarding overflow and drainage conditions made at the time of this examination do not entirely justify the precautions mentioned in this report but because of the evidence of drift, scattered about the fields, marks on fences and buildings, evidently made by high water, remnants of old levees and the numerous and extensive provisions that both the Northern Electric and the Southern Pacific have made for passing storm water, it is believed by the writer that the problem often assumes a rather serious nature. Intermittent overflow lasting probably only a few hours would not seriously interfere with the type of agriculture carried on at present but should this tract be subdivided and thickly settled, overflow would become quite serious.<sup>114</sup>

Mr. Weir, who made the report, recommended that some \$35,500 be spent for drains in order to prevent damage from winter floods. He emphasized that it was impossible to forecast how serious the problem might be. In February, 1919, the rainfall was heavy, and Mr. Kreutzer, recognizing the hazard involved, called in Mr. Weir and Mr. Williams to consider what should be done.<sup>115</sup>

<sup>112</sup> Wright, R. V. Letter to C. W. Cleary, February 27, 1929. (Files of California Department of Finance, Division of State Lands.)

<sup>113</sup> It must be noted that while these factors still cause serious losses on the settlements, many settlers who are growing crops adapted to the soils and who have good farm organizations are doing well.

<sup>114</sup> Weir, W. W., Drainage Engineer in the Experiment Station. [Report on drainage conditions on Stanford Tract.] December, 1917. (Typewritten; in files of W. W. Weir.)

<sup>115</sup> Kreutzer, Geo. C. Letter to Milo Williams, March 6, 1919. (Files of California Department of Finance, Division of State Lands.)

They recommended some extensive work, and there is good reason to believe that some money was allocated for the purpose. The funds, however, were evidently diverted to Delhi.<sup>116</sup> No important drainage system was ever developed.

#### DELHI PRODUCTION PROBLEMS

*Early Production Problems.*—At Delhi, the early experience was very different from that at Durham. It was described by the Board as follows:

As soon as the land was purchased the work of preparing for spring planting began. A large force of men were employed in leveling and checking land for alfalfa, in leveling land for vineyard planting, and in setting out vines. Three hundred and six acres were leveled and checked, and about one-half the acreage was planted to alfalfa. One hundred seventy acres were set out in vineyard....

Due to unusually strong winds in the spring of 1920, much damage was done to the land that had been prepared for irrigation. The work had started so late that it was impossible to take the ordinary precautions against wind damage, such as the planting of rye strips. Water was furnished to the land that had been seeded to alfalfa and had been planted to vines, through slip joint pipe in order to carry the plantings through until the regular irrigation system was completed. The showing that the alfalfa and vines made during the early spring indicated that the irrigation was efficient but wind damage was too great to overcome. No provision had been made against damage by rabbits, so that in a number of the vineyards the young shoots were eaten off by this pest. Rabbit wire was later put around one of the vineyards, but the vineyard had already suffered.<sup>117</sup>

While the danger from wind was reduced by handling only 1 to 5 acres at a time so that the crop may be growing before the wind rises (the growing crop will serve to break the wind and hold the soil in place), by planting rye strips to catch the wind and drift, and by disking in manure and straw to bind the soil,<sup>118</sup> many crops continued to be lost. Bamboo windbreaks were sometimes planted but they in turn became a pest. Blowing from adjacent vacant farms could never be stopped, and there were many such farms. This was particularly bad if the land had been broken but not put into crop. Some observers have claimed that farms should not have been sold except in solid blocks at one time so no such vacancies would have occurred. With sales as slow as they were, however, it is not clear that any different procedure from that followed was possible if settlers were to be allowed freedom of choice.

At first even where the alfalfa was not blown out by the wind, the crop was poor. This difficulty was corrected for a time by the application of sulfur and of ground limestone and sulfur, and by June, 1922, 1,369 acres had been planted to alfalfa along with 347 acres in trees, 343 acres in vines, and 100 acres in sweet potatoes.<sup>119</sup> At the end of three years some 2,000 acres were in alfalfa with a reported average yield of 4½ tons per acre. A few fields were producing 6 to 10 tons. With this feed available, a promising dairy industry was started.

<sup>116</sup> "The Land Settlement Board desires to have a re-allocation of the million dollar appropriation. Some of the money allotted to Durham and Berkeley will not be needed, while there is urgent need for all of it at Delhi. I should like, therefore, to have \$20,000 taken from the \$108,000 allocated to Durham for loans, and to have the \$30,000 allocated to Durham and not used, made available for use at Delhi and to have \$15,000 taken from the allocation to the Berkeley office and also credited to the Delhi fund." (Mead, Elwood. Letter to State Board of Control. September 17, 1920. Files of California Department of Finance, Division of State Lands.)

<sup>117</sup> California State Land Settlement Board. Report . . . September 30, 1920. *op. cit.* p. 34.

<sup>118</sup> California Department of Public Works, Division of Land Settlement. Report . . . September 1, 1922. *op. cit.* p. 42. <sup>119</sup> *Ibid.* p. 41.

To encourage this development of dairies, the United States Department of Agriculture stationed one of their men, Mr. C. V. Castle, at Delhi. High-producing grade or purebred Holstein cows and first-class purebred Holstein sires were brought in. The state and local banks furnished the settlers with credit so that shortly a number of farmers had some promising dairy enterprises under way. There were 211 grade cows and 32 purebred cows on the settlement in the summer of 1922. In July of that year, 115 of them had an average milk-fat production of 39.75 pounds. While that fall the State Department of Agriculture found 29 tubercular reactors, which had to be disposed of at a heavy loss, the dairy program continued to expand rapidly.<sup>120</sup>

It must be noted that the settlement officers, university technicians, and trained personnel from other agencies gave a great deal of help in organizing farms and in supervising cultural and animal-husbandry practices. Talks and demonstrations were given, farms were visited at frequent intervals, crops were inspected, and records were kept.<sup>121</sup> The most detailed records were kept for the Veterans Bureau trainees, for whom monthly budgets for two years in advance were set up.<sup>122</sup> The superintendents at both settlements were chosen largely because of the technical aid they could give the settlers. Mr. Packard states that the supervision was extremely detailed. Undoubtedly, the settlers, if they wished, had every assistance.

The returns from production, however, were inadequate. In the first place the important enterprises required heavy investments with no returns to be expected for a number of years. This was particularly true of trees but was also true of vines and alfalfa. Any returns from the last were often reinvested in a dairy herd and equipment. Second, production was often very poor. Inter-planting of trees and vines with cash crops, although advised, succeeded only at times. The settlers' experience with annual crops was such that on the whole they came to be considered a last resort. For most and perhaps all settlers it was impossible to meet interest, water, and principal payments and to make a living. As a result, delinquencies increased rapidly and the settlers demanded an adjustment of their debts. In 1925 this was granted with delinquencies eliminated and debts and interest rate reduced. The section on "Reorganization at Delhi" describes this adjustment in more detail.

*Later Production Problems.*—After this adjustment at Delhi in 1925, there was much hope that the settlement would prosper. The settlers had been on their allotments from three to five years and had had time to bring them into production; even the peach orchards should soon have begun to bring some returns. If the settlement could ever have succeeded it would have done so at this time. Nevertheless, during the next five years, the settlement became an almost complete failure, and the state gave up most of its investment. While there were many causal factors operating, production problems became even more dominant than before. In fact most of the alfalfa and orchards died.

The extent of these failures can be partly seen in the statistics of crop acreages at Delhi (table 1). With some minor exceptions, the area covered by these figures is identical with that of the land-settlement tract. The figures for 1927 and 1928 had been previously copied from records of the settlement office and may include some items not usually counted. The figures for both alfalfa

<sup>120</sup> *Ibid.* p. 41.

<sup>121</sup> *Ibid.* p. 45.

<sup>122</sup> Files of Giannini Foundation.

and trees were about 200 acres higher than other figures found. Crops not shown were minor and made no significant changes. Alfalfa reached its highest total of 2,400 acres in 1925, after which it declined to as low as 607 acres in 1931. Moreover, while in 1925 phenomenal yields were reported, in later years the yield was reported to be much less. The importance of this drop is reflected in the change in the dairy industry. New as it was in 1925, there were about 800 head of dairy cows and heifers in the settlement. In 1935, only three herds of any size were reported as being maintained. The acreage in trees reached its maximum of 1,491 acres in 1928, its minimum of 512 in 1932. The condition of part of this acreage in 1932 was reliably reported, moreover, as very poor. The

TABLE 1  
CROPS GROWN AT DELHI, 1922-1934

Year	Alfalfa	Trees	Vines	Beans	Corn
	acres	acres	acres	acres	acres
1922 . . .	1,300	374	347	...	.. .
1923 . . .	1,800	800	350	...	..
1924 . . .					..
1925 . . .	2,400	1,200	600	.	
1926 . . .					
1927 . . .	2,200	1,400	500	300	400
1928 . . .	2,200	1,491	637	300	450
1929 . . .	1,600	890	510	700	600
1930 . . .	673	762	398	1,193	358
1931 . . .	607	641	414	1,667	203
1932 . . .	807	512	422	1,490	1,032
1933 . . .	886	537	448	1,628	1,040
1934 . . .	904	574	484	1,613	1,039

Sources of data:

1922-1925: From the files of Delhi State Land Settlement Office

1927-1934: From the office of the Turlock Irrigation District

settlers, however, delayed pulling trees and plowing up alfalfa until an adjustment had been made with the state. Consequently a large total acreage was maintained longer than would otherwise have been the case. The acreage in vines made little change during these years. In 1927 beans and corn were unimportant but by 1932 they had become the two main crops in point of acreage.

The final situation at Delhi under state supervision is shown in an appraisal finished early in 1929. Table 2 shows the 1925 and 1929 valuations. It should be remembered that the 1925 valuations were considerably lower than the original contracts because the 1925 adjustment had provided for a 15 per cent reduction in the price of the land. In the 1929 appraisal, land was further reduced in value 56 per cent. The 1929 reduction in value of 80 per cent on trees and vines shows the seriousness of the production situation. The reduction of 31 per cent in the buildings was not to be unexpected for structures seven or eight years old; the heavy loss here was in poultry equipment. The largest absolute loss was in land. Some of the considerations in the appraisal at Delhi were as follows:

In making appraisals of the improved ranches we have arrived at values which an experienced farmer could afford to pay, and would be willing to pay, provided he desired to locate in the Delhi Colony.

In arriving at these conclusions we have taken into consideration the possible earning power of the lands under the management of an experienced farmer; the quality of the soil and its adaptability; the contour of the land and its location, the irrigation system, cost of water and time consumed in irrigating; the adequacy and inadequacy of the pipe line system; the general conditions of the community, economic and otherwise. We have also taken into consideration the demand for farm lands in this and other parts of the state, and the sale value thereof.

TABLE 2

THE 1925 AND 1929 AVERAGE VALUATIONS AND SHRINKAGE AT DELHI,  
BY TYPES OF ALLOTMENTS

Item	50 laborers' allotments, average 2.03 acres		52 poultry farms, average 6.34 acres		130 farms; average 30.52 acres		All 232 allotments, average 18.96 acres	
	Average valuation	Percent-age shrinkage	Average valuation	Percent-age shrinkage	Average valuation	Percent-age shrinkage	Average valuation	Percent-age shrinkage
	dollars	per cent	dollars	per cent	dollars	per cent	dollars	per cent
Land (piped and graded):								
1925 valuation . . .	775	.	1,845	.	8,094	.	5,116	
1929 valuation . . .	515		1,050		3,362		2,230	
Shrinkage . . . . .	260	34	795	43	4,732	53	2,880	56
Trees and vines:								
1925 valuation . . .	89	.	221		1,211		747	
1929 valuation . . .	12		28		249		149	
Shrinkage . . . . .	77	87	195	88	962	80	598	80
Buildings:								
1925 valuation . . . . .	903	.	1,404		1,701		1,402	
1929 valuation . . . . .	662		914		1,194		1,018	
Shrinkage . . . . .	241	27	490	35	507	30	446	31
Total:								
1925 valuation . . . . .	1,767	.	3,470	.	11,006	.	7,326	
1929 valuation . . . . .	1,189		1,990		4,805		3,394	
Shrinkage . . . . .	578	33	1,450	43	6,201	56	3,932	54

Source of data: Files of the State Land Settlement Office at Delhi.

We have not taken into consideration the cost of the pipe line, as in some cases the cost of the pipe line would exceed our appraised value of the land. The pipe lines are a part of the land, and a part of the irrigation system, and should not be added to our appraised value.

... we find many peach orchards badly diseased and a great number of them are being pulled out by reason thereof. Therefore, we have only allowed enhancement upon such orchards where we were satisfied that they were comparatively free from disease and showed fairly good production.

... there are very few good pieces of alfalfa in the colony.

In placing a value on building improvements we have figured the present cost of reproduction and allowed the usual depreciation, at the same time taking into consideration the present condition of the buildings.

On a great many of the allotments in the Delhi Colony there have been large sums of money spent for chicken houses and equipment connected therewith, and numerous poultry men have gone out of the poultry business and apparently do not intend to re-engage in such business. On these ranches the buildings are vacant and unoccupied and going to wreck and ruin, and such buildings are of no particular value to the ranch under the present method of operation. In appraising these buildings we have taken this factor into consideration.

Generally we have allowed an enhancement on Thompson Seedless Vines where it would not increase the value of the entire ranch beyond the prospective sale value, as the soil conditions generally seem to be adapted for the growing of this fruit.<sup>122</sup>

As a result of these production problems the settlers had to resort to annual crops of relatively small income-producing possibilities. This change was disastrous, since it was difficult to make even a living with beans and corn on the small farms of 20 to 30 acres, to say nothing of paying off heavy debts. The latter had to be reduced or the settlers would lose their homes.

The causes of these crop losses were physical and biological. The alfalfa failed to continue to produce a good stand or growth and soon died out. Soil deficiencies, diseases such as bacterial wilt, and nematodes, all played a part. The chief difficulty with the peach trees seemed to be little-leaf, although nematodes again were a factor. Cultural practices had little to do with the failures; the crops died regardless of the care given them.

*Information Available in 1919 about Delhi.*—The question that arises is how the Board came to purchase land subject to such serious production hazards. Why did men with access to the best advice buy the wrong sort of land on which to grow alfalfa and peaches? To answer the question a review is necessary of the information available to the Board at the time of purchase. This information included the 1917 report of their own investigators which, in part, was as follows:

The entire surface is largely wind-formed and possessed minor elevations, ridges and depressions characteristic of wind-formed soils....

Only one type of soil is present and that is a medium sand. The soil on the ridge crests and other elevated parts is usually somewhat coarser than that at lower levels. It is uniform to 6 feet or more in depth except for a few small intermittent spots containing thin layers of rather compact silty material at depths ranging from 3 to 6 feet below the surface. These compact layers resemble a feebly cemented hardpan in places and at times bear small calcareous nodules.

The sand in the depressions and other lower lying positions is a little more loamy and locally approaches a fine sand in texture. In these places the compact silty subsoil layers are more numerous and usually nearer the surface but they do not hinder the penetration of roots and water. In fact, they sometimes serve a beneficial purpose in checking the loss of water by percolation. The soil is loose and soft when dry and in the virgin state and tends to drift quite badly over exposed surfaces but when sown to crops and irrigated the surface packs quite firmly and is not affected by wind to any great extent. It is low in organic matter, absorbs water readily and is very easily tilled at all times of the year.

No alkali nor high water table is present in this tract, but the excessive use of water in the same kind of soil nearby has caused a rising of the water table in some of the depressions and an accumulation of small amounts of alkali.

The tract as a whole is very well drained and the soil retains moisture well.

Most of the land in the tract is still in the virgin state. That in use is utilized for rye, wheat, barley, and milo with low yields.

Under irrigation from 7 to 9 tons of alfalfa were produced per acre in 6 cuttings in part of Sec. 1 near Ballico. Here excellent pumpkins, sweet and Irish potatoes, melons, peaches, grapes, milo and other crops are produced.<sup>123</sup>

This description fails to stress certain features that had received consideration in the soil surveys which the United States Department of Agriculture

<sup>122</sup> Varner, J. E., and Wellington Brown. Appraisal report to State Land Settlement Board, February 1, 1929. (Files of State Land Settlement Office, Delhi, California.)

<sup>123</sup> Wank, M. E., W. E. Packard, and C. F. Shaw. [Report to State Land Settlement Board relative to Delhi Tract. 1917.] (Typewritten; in files of Giannini Foundation.)

had made of this area.<sup>125</sup> The eastern part of the area had been included in the Merced soil survey made in 1914 and the remainder in the Modesto-Turlock soil survey made in 1908. Figure 4 is based on these two soil-survey maps. The tract purchased is outlined in heavy lines. The major canals are shown as they existed in 1919—the High Line Canal, Lateral No. 6, and the Delhi Ditch, all a part of the Turlock Irrigation System. The area east of the High Line Canal was above the Ditch and had not been covered by the Turlock System. Because of the topography, some land west of the Ditch was also above it or at least was so high and rolling that gravity irrigation was not feasible. Most of the tract was wind-blown and therefore rolling.

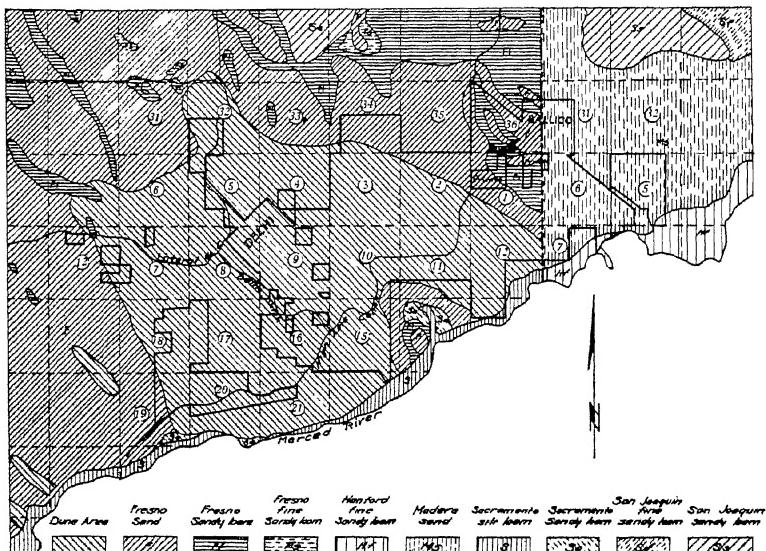


Fig. 4.—Soil types of Delhi State Land Settlement, as shown by soil survey of the Merced area for sections 5, 6, 7, and Ballico Townsite on eastern end, and as shown by soil survey of the Modesto-Turlock area for the central and western part.

According to the soil survey of the Turlock-Modesto area (fig. 4) the tract was largely of Fresno sand. Such was the classification of the dune area shown on the map as occupying the major portion. Its outlines are, to a surprising extent, identical with those of parts of the tract, especially along the western and southern edges. The most important exceptions are in sections 5, 6, 7, 8, and 17 of the western part of the tract. These exceptions were under either the Lateral No. 6 or the Delhi Ditch and pieces of them were level enough so that already they were under irrigation. Fresno sand, with no dune formation, is shown in sections 34, 36, 1, and part of 2; Fresno sandy loam in sections 36, and

<sup>125</sup> Sweet, A. T., J. F. Warner, and L. C. Holmes. Soil survey of the Modesto-Turlock area, California, with a brief report on a reconnaissance soil survey of the region east of the area. U. S. Dept. Agr. Bur. Soils, Field Oper. 1908:1-70. 1909. (Out of print.)

Watson, E. B., et al. Soil survey of the Merced area, California. U. S. Dept. Agr. Bur. Soils, Field Oper. 1914:1-70. 1916. (Out of print.)

Nelson, J. W., et al. Reconnaissance soil survey of the lower San Joaquin Valley, California. U. S. Dept. Agr. Bur. Soils, Field Oper. 1915:1-157. 1918.

1 near Ballico. The eastern part of the tract was mapped in the soil survey of the Merced area as Madera sand. Various loams appear between the Merced River and the southern edge of the tract.

The reconnaissance soil survey of 1915 is similar in many important respects. Although the dune area is not shown on the map, it is mentioned in the report. The Fresno sand of the Modesto-Turlock study is called Oakley and Fresno sands, undifferentiated. In sections 36 and 1, the soil called Fresno sandy loam in the Turlock-Modesto survey is called Fresno sandy loam, brown phase—only as additional detail in description. There are also some variations in the boundaries of these types. It should be noted that this survey states that, "In all cases the topography is favorable to agriculture."

The report to the Board and the reports of the soil surveys differ in two notable respects. First, according to the surveys the soil around Delhi, although resembling that of adjacent areas, differs in containing more sand and in having a rolling, irregular topography; in short, it has a sand-dune character. Because of this difference the land at Delhi could not be compared exactly with the adjacent land which was being irrigated and intensively cultivated.

This difference is illustrated by its history. Some of the sand-dune land had never been farmed satisfactorily. The farmers in that vicinity regarded the best as old, worn-out rye land, the poorest type that they ever cultivated. Occasionally a crop could be grown in the northeastern part, where the Fresno sandy loam or Madera sand predominates. Rental returns were low; contracts usually called for one fifth of the crop and returned about 50 cents an acre to the owner.<sup>126</sup> In 1919 most of the land was assessed at \$20 an acre, a little at \$23, and a considerable amount as low as \$12.<sup>127</sup>

Irrigation had been found profitable on only a few isolated level places. In 1911 the town of Delhi was plotted and all the area under the Turlock High Line Canal was subdivided. Of the part sold, the assessor's records show that much came back to Mr. Wilson. Later the area around Ballico was subdivided but very little was sold to settlers. Altogether some 200 acres had been thus developed adjacent to Lateral No. 6 and the Delhi Ditch. Elsewhere settlers found it impractical to irrigate. Dr. Mead described the physical situation found there as follows:

Its lack of development and the price at which purchased was due to the sandy and broken character of the land making it difficult to prepare for irrigation and hard at the start to grow crops.

.... the surface of this area is too undulating for transporting water in open ditches. Last season an irrigator who tried it had to employ three men to watch the ditch banks and prevent breaks while one man distributed the water.<sup>128</sup>

Such information doubtless led the engineers after the purchase to change their plans for laterals from ditches to pipes. Certainly some marked differences existed between the Delhi tract and the near-by irrigated lands. This conclusion is borne out by the second notable difference between the report to the Board and the various soil surveys: the former does not mention the

<sup>126</sup> California Department of Public Works, Division of Land Settlement Report.... September 1, 1922. *op. cit.* p. 40.

<sup>127</sup> Files of Assessor's Office, Merced County, Merced, California.

<sup>128</sup> California State Land Settlement Board. Report.... September 30, 1920. *op. cit.* p. 26.

Fresno sandy loam soil in the north-central part of the tract. There is considerable difference between this sandy loam and the prevalent sand of the tract. According to the mechanical analysis given in the soil surveys, the Fresno sandy loam contains less fine sand (26.8 per cent) and more silt (32.7 per cent) than the Fresno sand (41.1 per cent fine sand and 7.4 per cent silt). The structures of the two soils are also different. The sand is loose at the surface and does not compact after rains, whereas the sandy loam is sticky when wet, puddles easily, and forms a crust when dry. The Madera sand, being very similar to the Fresno sand, also differs from the sandy loam. The important point to this is that the report to the Board mentions excellent crops of alfalfa, potatoes, melons, peaches, grapes, and milo in part of section 1 near Ballico. All the evidence indicates that these crops were grown on Fresno sandy loam. Since this soil is shown by the survey reports to differ markedly from Fresno and Madera sands, the report to the Board regarding crops did not necessarily indicate what could be raised on the major portion of the tract.

Certain specific crop diseases and pests were found at Delhi and the question arises whether they were known in 1919. Nematodes, which seriously affected both peaches and alfalfa, were a widely known hazard. In 1911, Dr. E. A. Bessey of the United States Bureau of Plant Industry reported on the problem as follows:

The disease of plants known as root-knot, beaded root-knot, root-gall, eelworm disease, big-root, and probably under other names has been present in the United States for many years and has caused losses whose extent can not be calculated.<sup>129</sup>

....the root-knot is to be found....at many points in California.<sup>130</sup>

Root-knot is essentially a disease of light soils. Wherever the soil is sandy or contains a fairly large proportion of sand, other conditions being favorable, the root-knot nematode may be expected to thrive when once introduced.<sup>131</sup>

The subject was also covered in a Farmers' Bulletin of 1915,<sup>132</sup> in which a list of "the more important highly susceptible plants" included alfalfa, Old World grapevine, and peach trees. As to control, the authors made the following statements:

In orchards,....no entirely satisfactory method of control has been worked out. ....Never plant an orchard on land that is not known to be nematode free. Do not plant infested nursery stock on either clean or infested soil.

The most satisfactory method of combating the nematode in fields not planted to perennial crops is by the cultivation of immune crops for a period of two to three years and by carefully killing all weeds and susceptible plants in which the nematode can live. ....

Starving the nematode by keeping the land free from all vegetation for two years is an effective control method, though often impracticable.<sup>133</sup>

There is plenty of evidence that soil and plant specialists were generally aware of the nematode problem. Some of the studies made, moreover, applied directly to California crops, such as sugar beets and citrus, the latter having been studied by a member of the University staff.<sup>134</sup> The California Commission

<sup>129</sup> Bessey, Ernst A. Rootknot and its control. U. S. Bur. Plant Indus. Bul. 217:7. 1911.

<sup>130</sup> *Ibid.* p. 23.

<sup>131</sup> *Ibid.* p. 41.

<sup>132</sup> Bessey, Ernst A., and L. P. Byars. The control of root-knot. U. S. Dept. Agr. Farmers' Bul. 648:8. 1915.

<sup>133</sup> *Ibid.* p. 19.

<sup>134</sup> Thomas, E. E. A preliminary report of a nematode observed on citrus roots and its possible relation with the mottled appearance of citrus trees. California Agr. Exp. Sta. Cir. 85:1-14. 1913. (Out of print.)

of Horticulture reported on the problem in 1913, and alfalfa, grapes, and peaches were listed as susceptible to serious injury. "Young peach . . . are often killed outright by this pest if planted in a worm-infested soil."<sup>125</sup> It reported further that:

In the United States the distribution is decidedly spotted and it is at present regarded as a serious pest, and a menace to agriculture in only a few rather definite localities, especially in irrigated regions, the most prominent of which is an irrigated, potato-growing district in Nevada, where the depredations of the pest threatened the industry. The fact that the eel-worm exists in so many places, doing little appreciable damage, is no criterion that all necessary care should not be exerted in checking any further distribution of the pest. *Heterodera* is a comparatively new-comer to our soils, and the maximum amount of injury which it is capable of inflicting has undoubtedly not been reached. Intensive farming and more thorough irrigation are two factors which, in creating a better environmental condition, are decidedly advantageous in increasing the number of worms which the soil may harbor.<sup>126</sup>

This last statement indicates that while the root-knot nematode might very well have been considered a danger to areas such as Delhi, the character of the problem was not yet widely understood. This seems to be further indicated by the experience at Delhi where the nematodes were extremely harmful to peaches. They were also found in alfalfa, and in the 1920's evidently were regarded as an important cause of the failure of this crop. More recently, however, while nematodes are still regarded as a serious menace for older type peach rootstocks in sandy soil,<sup>127</sup> alfalfa is reported as giving a profitable crop even when infested by the root-knot nematode.<sup>128</sup>

The most important cause of alfalfa failure, according to the opinion of most observers, was bacterial wilt. This disease is caused by a bacterium which works from the soil into the plant. Its effect is severe because it often shortens the life of a stand one half or more. More seedings are required, poorer yields and quality are obtained, and a rotation with other and usually smaller-income crops is necessary. Authorities state that there is no really satisfactory means of controlling the disease.<sup>129</sup> It was first found in California in 1925, close to the Delhi settlement, and consequently could not have been anticipated.

Peaches were injured not only by nematode but also by little-leaf. This was a known hazard, particularly in sandy soil. As early as 1911 the California Agricultural Experiment Station reported on the disease as it affected peach trees, as follows:

Always worst on lighter, drier soils, this feature showing itself by the more pronounced occurrence of the disease on trees standing in sandy streaks or slight elevations in the orchard.

The typical peach disease has been seen only in the San Joaquin Valley, in the most sandy regions.

The trees fail to leaf out properly in the spring and seem to become confused, so to speak, as to the season. Later in the summer the trees may bloom and leaves begin to appear, but

<sup>125</sup> Childs, Leroy. Root-knot—cause and its control, including a list of susceptible host plants. California Commr. Hort. Mo. Bul. 2(12):741. 1913.

<sup>126</sup> *Ibid.* p. 737.

<sup>127</sup> In recent years the development of nematode-resistant rootstock has largely corrected the problem for peach trees. (Philp, Guy L., and Luther D. Davis. Peach and nectarine growing in California. California Agr. Ext. Cir. 98:19. 1936.)

<sup>128</sup> Tyler, Jocelyn. The root-knot nematode. California Agr. Exp. Sta. Cir. 330:12. 1933.

<sup>129</sup> Weimer, J. L., and B. A. Madson. Alfalfa diseases in California. California Agr. Exp. Sta. Cir. 326:6. 1932. (Out of print.)

the tops usually die back nearly to the forks of the tree and sometimes the trees die entirely....

.... Every few years there is usually a season, especially in the southern part of the State, when deciduous trees are badly affected in such ways as these<sup>140</sup>

In 1917 the disease was again reported on, this time in connection with grapevines. The reference is apt, however, in that, as the author of this report says, "... trees, such as peach, .... show similar symptoms."<sup>141</sup> Moreover, it is now generally agreed that peach trees are much more seriously affected than are vines. The report is as follows:

"Little-leaf" is a disease of the vine, varying in seriousness with oidium and phylloxera. It is confined to sandy soil in the great valley south of Sacramento County....

In severe cases the vines die after a few years. Vines slightly affected set fruit imperfectly, and those badly affected bear little or nothing.

No parasite has been found connected with the disease, and the evidence seems to show that it is not infectious. Several species of trees are affected with similar symptoms when growing near or among affected vines, indicating that the disease is due to local conditions of soil, water, temperature, or other non-parasitic causes.

No effective method of treatment has been demonstrated....<sup>142</sup>

Typical or serious cases of little-leaf have been noted only in sandy or sandy-loam soils. If one passes through an infected region, the disappearance of the disease with a change from sandy to clay soil is very noticeable.<sup>143</sup>

Thus little-leaf was a known hazard and was related to sandy soils. The people concerned with the appraisal, however, did not realize its importance. It turned out to be a very serious problem.<sup>144</sup>

#### AVAILABILITY OF LAND

In view of the experience at the two settlements a question may be raised as to why those particular tracts were purchased, and whether or not some other tracts might have proved more feasible. No real understanding of this is possible unless a review is made of the other available tracts.

The Board, in advertising for land, had in mind certain requirements. The tract was to be a compact unit large enough to merit the attention of a resident superintendent and suitable for irrigation development and intensive agriculture. In the purchase at Durham the plan was to develop a general livestock type of farming. The fruit later grown there was not in accordance with the original program. At Delhi, apparently, the community was to specialize in fruit raising.<sup>145</sup> Just how definite these ideas on enterprises were cannot be determined, although some people claim that certain tracts were refused as not suitable for the type of farms desired. Also, when the Delhi tract was purchased it was considered best, from both the political and the demonstration viewpoints, to buy outside the Durham area.

The lands offered the Board for the first colony consisted of 40 separate

<sup>140</sup> Smith, Ralph E., and Elizabeth H. Smith. California plant diseases. California Agr. Exp. Sta. Bul. 218:1151-53. 1911. (Out of print.)

<sup>141</sup> Bioletti, Frederic T., and Leon Bonnet. Little-leaf of the vine. Jour. Agr. Res. 8(10): 384. 1917. <sup>142</sup> *Ibid.* p. 397. <sup>143</sup> *Ibid.* p. 383.

<sup>144</sup> In recent years the development of zinc sprays has largely corrected the problem. (Philp, Guy L., and Luther D. Davis. Peach and nectarine growing in California. *op. cit.* p. 45.)

<sup>145</sup> California Department of Public Works, Division of Land Settlement. Report . . . September, 1922. *op. cit.* p. 43.

tracts totaling 199,089 acres. For the second colony, 64 offers were made, totaling 515,547 acres. Most of these tracts, however, were unfit; many had little or no water; others had poor soils with alkali or hardpan. According to Professor Shaw,<sup>146</sup> 6 tracts in the first group and 10 in the second could have been considered for purchase. Delhi and Durham, however, were preferred for a number of reasons. Faults in the water right or the cost of pumping or bringing in water excluded several. On one ranch near Fresno, for instance, not only did the water lift for pumping prove high but the supply was uncertain. For another tract at Hamilton City the price was \$200 an acre, and the seller laid down the impossible condition that the Board buy a sugar-beet mill at the same time. A tract at Union Island otherwise desirable, was thought to be in danger from flood. Perhaps the most valuable land rejected was the Holland Tract which today is a rich sugar-beet area. At that time, however, the irrigation system was just being developed, there was no assurance of adequate drainage, and the Board considered that there was danger from flood. Some claimed that it did not appear to be a good fruit area, which was what the Board desired. At that time it seems to have been regarded by many as a rather risky proposition. Even now, one can only speculate how satisfactory it would be divided into 30-acre farms.<sup>147</sup>

Since one or two of these areas have turned out to be very productive, the members of the Board have been subjected to severe criticism for their choice of Delhi. From the standpoint of present-day information it is easy to point out errors made in 1919. A judgment based upon the information presented to or available to the Board is much more difficult. In this light, the best of the rejected tracts do not appear so favorable as they do now, and the choice of Delhi appears to have been a reasonable one, if it is assumed, of course, that one of the tracts had to be purchased.

It is also commonly believed that the Durham choice was a very desirable one. A contrary view must be taken in view of the available information on production. Neither settlement has much choice over the other.

If the two tracts are regarded as poor choices, it must be emphasized that the other offerings also appear to have been poor, in spite of the fact that the Board canvassed the state thoroughly. Only one tract is known which they regarded as suitable but which was not for sale. It is sometimes said that the Board did not have sufficient funds to finance the purchase of the higher-priced lands. Quite the contrary seems to have been true. The Board invariably considered offering a larger down payment than was asked for. There is every reason to believe that the Board purchased what they thought were the best tracts available. It is a fact of great significance that although the proponents of land settlement had talked of millions of acres awaiting development (see p. 403 and 410), the experience of the Board indicated that there were few, if any, tracts that were suitable for their program of group settlement.<sup>148</sup>

<sup>146</sup> Mead, Elwood, C. F. Shaw, R. L. Adams, and J. W. Gregg. Colonization and rural development in California. *op. cit.* p. 34.

<sup>147</sup> It has been very difficult to discover the reasons for the rejection of the various tracts. There are marked differences of opinion among those acquainted with the selections.

<sup>148</sup> This may seem to be at variance with later developments where large acreages have come into intensive production. While these developments are beyond the scope of this study, it is believed that either they have been of a size not suited to the Board's requirements or have been made possible by technical and economic changes. Further investigation is needed.

Indicative of this lack of land is the fact that in order to buy the tracts selected, the Board had to pay prices that yielded high profits to the sellers. Judge Lott had received his land as a fee from a client some fifty years before when it had little value. Mr. White, who negotiated the sale to the Board, had an option which called for \$150,000 on this tract and on another tract of 400 acres. By this sale he received \$15,000 in cash and the 400 acres free of debt. Altogether his profits were \$40,000 to \$50,000.<sup>149</sup>

Mr. Wilson had begun to buy his land about 1905, much of it for about \$10 an acre.<sup>150</sup> Even with the addition of taxes and the expenses of attempts at subdivision, he made a handsome profit in his sale at \$92.50 an acre. The high price obtained was due to the speculative situation that prevailed in 1919. Everywhere land was bringing very high prices. The complicated nature of speculative values is shown by evidence that a few months before the sale, Mr. Wilson offered the area to a company for \$75 an acre. Similar evidence reveals that he was being offered \$100 an acre by an agency acting for a Japanese colony at the time he sold to the state.

The state had to pass these profits on to the settlers as costs which were among the most important they had to meet. The productive situation at Delhi, however, was so poor that even if the land had cost nothing the only effect would have been to reduce the capital losses sustained. Very nearly the same situation prevailed at Durham. The cost of the land purchased, while indicative of the lack of land, is secondary in importance to the fact that only poor land was available.

### THE ECONOMIC SITUATION

During the period under survey, that is, 1917 to 1930, the national price structure underwent some important changes. World War I and the post-War boom lifted all prices to unprecedented heights. The subsequent depression brought prices in general nearer the pre-War level. During these changes, agricultural prices fluctuated more than other prices. The effects of this widespread economic situation on the California State Land Settlements may be grouped under four headings: construction costs; produce prices; land sales; and land prices.

#### CONSTRUCTION COSTS

Figure 5 shows some indexes of construction costs for the United States at the time when construction on the two tracts was decided upon, and during the periods of construction. These periods can be defined only roughly. Construction at Durham, though largely completed during 1918 and 1919, continued as needed or as the settlers could afford it. At Delhi, construction began in December, 1919, and was almost ended in the spring of 1923; it was heaviest from the summer of 1920 to the summer of 1922. The indexes, charting variations in farm wages, and in prices of lumber, cement, and building materials for other than house, indicate in general the changes that the Board and settlers encountered.

<sup>149</sup> Furlong v. White. (1921) 51 Cal. App. 265. Appellate Records, Third District, Civil 2267. (See especially appellant's opening brief, p. 1-28; and reply brief of respondents, Elwood Mead *et al.*, as members of and constituting the State Land Settlement Board, p. 1-42.)

<sup>150</sup> Wilson, Edgar M. Interview. December 8, 1934.

As these indexes are for the whole United States, they cannot be regarded as giving an entirely accurate picture of conditions in specific parts of California. The lumber index, for one thing, may be faulty; a lumber war throughout the San Joaquin Valley during this period is said to have lowered lumber prices there disproportionately. Wages in California may have been higher than elsewhere in the United States. Another circumstance that may affect conclusions drawn from figure 5 is that the wages were paid largely to the settlers themselves who often turned the money back into materials. High or low

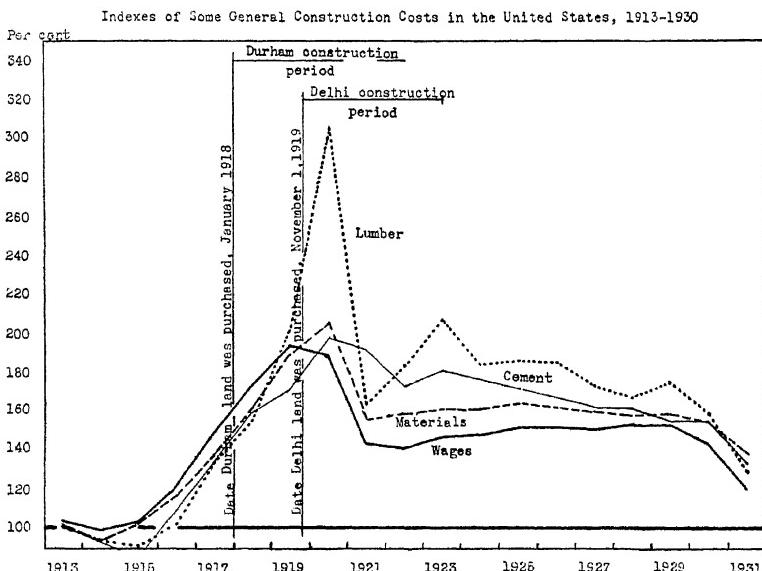


Fig. 5.—Indexes of some general construction costs in the United States, 1913-1930.

Data from: index of farm wages paid to hired labor (1910-1914=100), United States Department of Agriculture; index of prices paid for building material for other than house (1910-1914=100), United States Department of Agriculture; index of prices paid for lumber (1918=100), United States Bureau of Labor; index of prices paid for cement (1918=100), United States Bureau of Labor.

wages, consequently, merely affected the amount of money that would be used as wages and the amount that would be used as loans.

The data do, however, indicate price changes in a general way, and it is apparent that Durham was hard hit by rising prices for materials and labor, because they were much higher at the time of construction than when the land was purchased. The Board had to provide more money and the settlers incurred a considerably heavier debt than they had anticipated. Many settlers postponed construction but this delay may have increased costs as much as it lowered them, the amount depending on the time when construction was finally carried out.

This increase in construction costs at Durham, from the viewpoint of the Board, was more than compensated for by the situation at Delhi where the experience was just opposite. Prices for materials and labor were almost at their peak when the state purchased the land and estimates were made, and

in most cases, they were lower when the heaviest construction was under way. Consequently the Board and the settlers did not require so much money as the initial price situation would have indicated. Since the amount of construction carried out at Delhi was several times greater than that at Durham, the total effect of price changes in materials and labor must have been favorable to the Board.

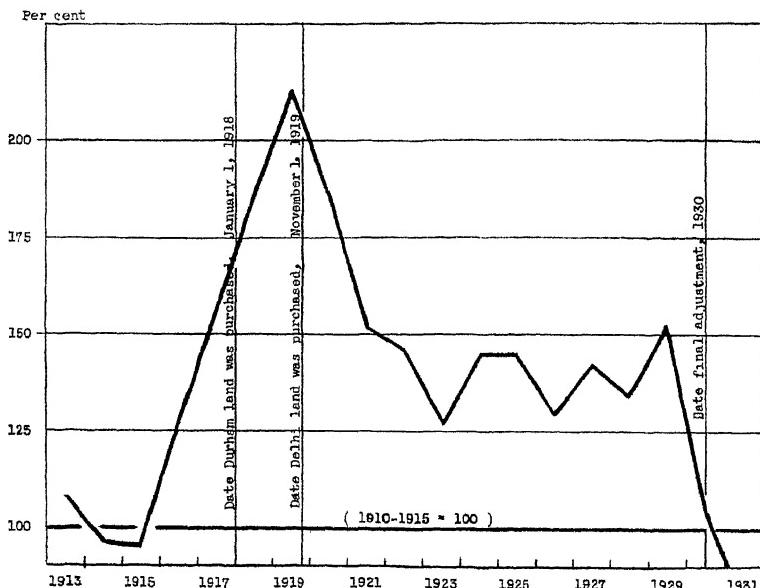


Fig. 6.—Annual index numbers of farm prices in California, 1913-1931.

Data from: Stover, H. J. Annual index numbers of farm prices, California, 1910-1938  
California Agr. Exp. Sta. Bul. 569:27. 1934.

#### PRICES OF FARM PRODUCTS

Figure 6 shows the index numbers of farm-produce prices in California during the period under consideration. At Durham during the first two years, changes in the price levels of farm produce made farming more profitable than usual.

The 1920 break in prices was expected to be only temporary and at first neither the settlers nor the administration realized how serious the situation would become. Many of the settlers at Delhi purchased after the drop in price but did not realize its significance. Those who had crops to sell felt the effect of the price fall immediately and beyond doubt a number of settlers, particularly at Durham, were seriously hurt by it.

The settlers at Delhi who planted raisin grapes were also hurt by the drop in prices. As previously mentioned (p. 431) Thompson Seedless grapes were productive. Even in this crop the Board found itself held responsible for serious losses because, with Prohibition established, it had advised the planting of raisin varieties in preference to wine varieties. The price drop, however, while very severe for raisins was relatively moderate for wine grapes. The

comparative price changes are shown in table 3. A couple of settlers, who had refused to take the administration's advice and had planted wine varieties, received a much better price for their product. The influence of the drop in prices on the settlers' income, however, should not be overemphasized. In view of the production difficulties encountered at both colonies, it is clear that most of the farmers had little to sell at any price.

TABLE 3

CALIFORNIA FARM PRICE OF WINE AND RAISIN GRAPES PER FRESH TON  
AND INDEX NUMBERS SHOWING CHANGES, 1919-1929\*

Year	Wine varieties		Raisin varieties	
	Price per fresh ton	Index	Price per fresh ton	Index
1919 . . . . .	<i>dollars</i>	<i>1919-1921=100</i>	<i>dollars</i>	<i>1919-1921=100</i>
1920 . . . . .	50	72	52	100
1921 . . . . .	75	109	64	123
1922 . . . . .	82	119	40	77
1923 . . . . .	65	94	19	37
1924 . . . . .	40	58	13	25
1925 . . . . .	63	91	17	33
1926 . . . . .	60	87	20	38
1927 . . . . .	45	65	17	33
1928 . . . . .	45	65	17	33
1929 . . . . .	25	38	10	10
	35	51	16	31

\* Returns to growers for naked (unpacked) fruit delivered at growers' first delivery point.  
Source of data:

Shear, S. W. Deciduous fruit statistics as of January, 1942, p. 68. Univ. of California Giannini Foundation. (Mimeo.)

## LAND SALES

Although the Board had confidently expected a strong demand for farms, even the most energetic sales program failed to bring in settlers, and over one third of the land at Delhi was unsold. There appear to be two significant reasons for the almost complete breakdown of sales in the settlement: the national economic situation and the settlement production difficulties.

After the depression of the early twenties, there was a falling off of land sales throughout the United States and a revulsion from the "back-to-the-farm" movement of War and pre-War times. Although California was not so much affected by this trend as was the rest of the country, there is no doubt that this widespread situation was influential at Delhi. It not only slowed the inflow of applicants, but changed the attitude of the Legislature; agricultural development was no longer considered so important as it had been.

Figures available for California indicate, however, that this national situation was not so important in the failure of the Delhi sales program as was the production situation. For instance, the number of farms in Merced County, according to the 1930 Census, rose from 2,846 in 1920 to 3,722 in 1925 and 3,830 in 1930. The number of farms in Stanislaus County rose from 4,566 in 1920 to 5,177 in 1925 and 5,743 in 1930. The number of taxpayers in the Turlock Irrigation District became greater every year, increasing from 5,491

in 1920 to 7,029 in 1925. Since these figures refer to areas immediately adjacent to the Delhi tract, it seems reasonable to believe that the difference between land sales at Delhi and in the surrounding area was caused by local difficulties—namely, the production problems just described.

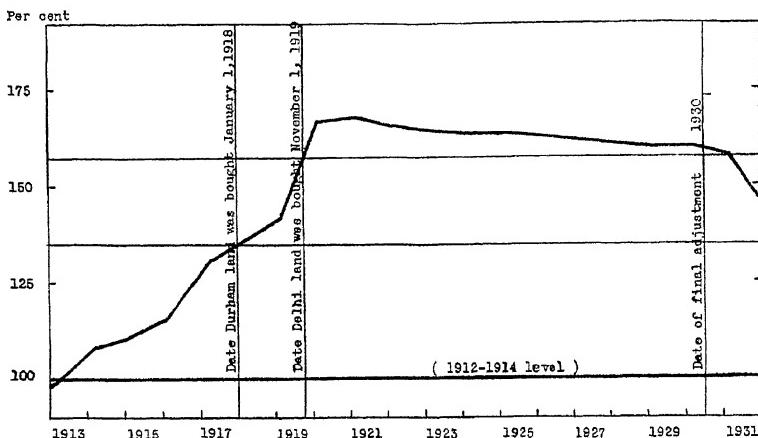


Fig. 7.—Farm real estate: index of estimated value per acre, California, 1913–1931. Data from United States Department of Agriculture, Farm Real Estate Situation, annual issues.

#### LAND PRICES

Figure 7 shows the annual index of value of land in California as estimated by the United States Department of Agriculture from 1912 to 1932, and the index of estimated values when the tracts for the two settlements were contracted for by the Board. It shows, first, that land values during the period

TABLE 4  
AVERAGE VALUES OF FARM LAND AND BUILDINGS PER ACRE

Year	Butte County	Merced County	Stanislaus County
1910 .....	<i>dollars</i> 44.19	<i>dollars</i> 36.47	<i>dollars</i> 59.51
1920 .....	<i>dollars</i> 102.04	<i>dollars</i> 77.77	<i>dollars</i> 128.55
1925 .....	<i>dollars</i> 85.27	<i>dollars</i> 97.09	<i>dollars</i> 144.57
1930 .....	<i>dollars</i> 77.98	<i>dollars</i> 82.01	<i>dollars</i> 126.45

Sources of data:

1910, 1920, and 1925: U. S. Bureau of the Census. United States Census of Agriculture, 1925, vol. 3:455–82, 1927.

1930: U. S. Bureau of the Census. Fifteenth Census of the United States, 1930. Agriculture. The western states, vol. 2(3): 528–31, 1932.

studied were much higher than the 1912–1914 level; second, that this particular land was bought while prices were rising, but before they reached their peak; third, and most important, that the index of prices at the time of the purchase was less than any succeeding index until after the state severed its connection with the settlements. Evidently the Board had a margin at all times as far as the general trend was concerned.

Variations in the value of land in the counties containing the settlements or immediately adjacent thereto, according to the United States Bureau of the Census, are shown in table 4. In Butte County values declined decidedly between 1920 and 1925, though not enough to wipe out the rise that had occurred after the Board bought the Durham land in 1918. In Merced and Stanislaus counties, where Delhi was situated, values rose considerably between 1920 and 1925, although most of the gain had been wiped out by 1930. Thus the census data, as well as the United States Department of Agriculture estimates, indicate that land prices in general were sustained during the period. There is little justification for any supposition that reduced land prices in areas near the settlements drew applicants away from Delhi. More important, the maintenance of land prices indicates that there was a continuing demand for land throughout the period under consideration and supports the conclusion that the failure of sales at Delhi was due largely to production difficulties there.

### FINANCIAL PROBLEMS

Several means and sources were used in financing the settlements. For one thing the previous owners of the Stanford tract and of most of the Delhi tract asked for a down payment of only part of the purchase price. The settlers, particularly those at Durham, furnished an important part of the money needed. The Federal Land Bank gave considerable aid. Local banks and some other organizations added small amounts. The state, however, was the most important source. In 1917, \$10,000 was appropriated for administrative purposes and \$250,000 was set up as a revolving fund.<sup>151</sup> In 1919, \$1,000,000 was added to this fund, and in 1921 another \$1,000,000 was added.<sup>152</sup> All the evidence indicates that the Legislature during these years gave everything that the Board asked.

The general condition of purchase included a 5 per cent down payment on land and a 40 per cent down payment on improvements. Land and improvement loans were made at 5 per cent and on amortization contracts of thirty-six and a half years for land and twenty years for improvements. But, only a straight five-year loan was allowed on livestock and equipment, and cash was required for any expense incurred by the Board in planting crops.<sup>153</sup> An exception to the time required was made on the Stanford tract. Since it had been purchased under a twenty-year contract the Board required a similar twenty-year contract from the settlers.<sup>154</sup> The Board gave deeds to the Durham settlers. Because of the current rise in governmental expenditures and because of the local improvements, the settlers had to pay unexpectedly heavy taxes. This aroused some criticism from the settlement officers and to avoid a similar experience at Delhi they decided to give only contracts of purchase there. Consequently the state continued to hold legal title to the land and it was exempt from taxation.

The capital requirement for those going on farms was at first \$1,500,<sup>155</sup> later

<sup>151</sup> California Statutes, 1917. Chap. 755.

<sup>152</sup> California Statutes, 1919. Chap. 450.

<sup>153</sup> California Statutes, 1921. Chap. 15 and Chap. 734.

<sup>154</sup> California Statutes, 1919. Chap. 450, Sec. 18.

<sup>155</sup> California State Land Settlement Board. Report... June 30, 1918. *op. cit.* p. 8.

<sup>156</sup> *Ibid.* p. 9.

\$2,500,<sup>126</sup> and again \$1,500 in 1923.<sup>127</sup> A down payment was all the capital that was required of those desiring laborers' allotments. These were very easy to purchase. The land cost from \$120 to \$780, and credit terms were the same as for farms. On an allotment costing \$400 the required down payment was \$20; one of the most successful men at Durham is said to have made a down payment by selling his watch.

#### FINANCING AT DURHAM

*Capital Supplied by Settlers.*—A fairly definite picture can be given of the capital possessed by settlers at Durham. Mr. Kreutzer, the superintendent, made a survey there in 1924, the record of which shows the status of 83 farmers, both as listed at the time of application and as corrected in 1924 for losses on land and on other assets owned outside the settlement. The average amount brought in by this group was \$5,645.<sup>128</sup> Besides their initial capital, the newly arrived settlers were able to earn some additional money by working on construction; several earned \$1,000 or more in this way. Also, many purchased farms with growing crops on them; 11 settlers thus received an average of \$534.51 over all costs of planting, harvesting, and threshing.<sup>129</sup> On the whole, the settlers at Durham made an important contribution to the capital required. This amount, moreover, gives a very favorable impression of the character of the settlers there.

*Financial Situation in 1924.*—The general impression over the state during the early years was that the settlement at Durham was a success. This favorable impression was largely due to ignorance of the fact that many farmers were delinquent. From the very first, delinquency was common and as the years went by it became a greater and greater problem.

The year 1924 is chosen for a detailed description of the situation. There are a number of reasons for the choice: For one thing the original administration was in charge up to the summer of that year. Except on the adobe lands, and on a few other farms, crop losses do not seem to have become serious until about this time; consequently, poor yields cannot be held to be generally responsible for delinquency. Moreover, and of great importance, there are several reports available for that year. The state auditor made a detailed analysis. Mr. Kreutzer made an inventory of each farm. The 1925 Census of Agriculture covers this same year. In coöperation with the United States Bureau of the Census, the Bureau of Agricultural Economics and the Bureau of Public Roads Division of Irrigation obtained detailed data from settlement farms for a study of the economic limits of cost of water.<sup>130</sup> These various sources provide an excellent picture of the situation.

The state auditor made a detailed financial report on the Durham settlement as of February 29, 1924. The total balance amounted to \$805,493.01. The liability side had as its principal items a debt to Stanford University of

<sup>126</sup> California Department of Public Works, Division of Land Settlement. Report . . . September 1, 1922. *op. cit.* p. 14.

<sup>127</sup> Mead, Elwood. Letter to R. M. Morton, Director of Public Works. Sacramento, California, March 3, 1923. (Files of Giannini Foundation.)

<sup>128</sup> Files of Giannini Foundation.

<sup>129</sup> California State Land Settlement Board. Report . . . June 30, 1918. *op. cit.* p. 11.

<sup>130</sup> Teele, R. P., and Paul A. Ewing. The economic limits of cost of water, the Durham State Land Settlement, California. *op. cit.* p. 1-30.

\$225,525.37, a debt to the state of \$398,821.74, and a surplus of \$143,792.58. The assets included \$5,403.14 in cash, \$73,498.00 due and delinquent from settlers, \$587,879.29 in unmatured claims against settlers, \$21,004.01 due from Delhi, \$73,947.83 as the value of unsold farm allotments, and \$31,348.11 as the value of reserved lands.

The book surplus of \$143,793.58 shown in this statement was largely a provision for future administrative costs. It was offset, however, by the fact that some assets were of doubtful value. The farm allotments unsold, valued at \$73,947.83, consisted of 9 farms totaling 660.65 acres. The valuation of the land of 5 of these farms had been reduced from the original \$49,577.02 to \$37,286.40 because of the adobe soil. Although most of these farms were leased,

TABLE 5  
NUMBER OF SETTLERS DELINQUENT AND NOT DELINQUENT AT  
DURHAM STATE LAND SETTLEMENT, BY SIZE OF  
ALLOTMENT, FEBRUARY 29, 1924

Size of allotment			Settlers not delinquent	Settlers delinquent
	acres	number		
0- 2 99		20		7
3-14 99	.. . . . ..	12	3	
15-29 99	.. . . . ..	11	16	
30-64 99.....	.. . . . ..	11	30	
65 or over.....	.. . . . ..	2	16	
Total.....	.. . . . ..	56	72	

Source of data:

California Department of Finance, Division of Budgets and Accounts,  
[Report on the Durham State Land Settlement as of February 29, 1924]  
(Typewritten.)

they were not repaying the investment the state had in them. The item of \$21,004.01 due from Delhi was virtually worthless. The matured and unmatured claims against settlers were the important assets of the settlement and will be described in detail.

Throughout this analysis a delinquency of less than \$15 will not be considered. There were several of them but they appeared to be so minor that their inclusion would tend to be misleading. Consequently the total of delinquencies studied in the following tables is not exactly the same as shown in the auditor's report. Table 5 shows the number of delinquencies by size of allotments. The striking features here are that there were more farms delinquent than not delinquent and that delinquency was much less frequent on the smaller allotments than on the larger. Whereas on the smallest allotment, the proportion of nondelinquents to delinquents was 20 to 7, on the largest it was 2 to 16.

Table 6 shows the indebtedness of settlers at Durham by size of allotment and by delinquency. The greater delinquencies of the larger allotments are again emphasized. The groups having the largest delinquency also had the heaviest unmatured indebtedness. The settlers who were behind in their payments had an unmatured indebtedness of \$450,636.48, or 76.7 per cent of the total unmatured amount due the state.

Elsewhere in this study (p. 425), it is emphasized that the farms were too small for profitable farming. This may seem to be contradictory to these details on the farmers' debts at Durham. While no attempt has been made at a farm-management analysis of the settlement farms, the seeming contradiction seems to be largely due to the facts that the smaller farms were on better soils and that the men on smaller allotments had time to work elsewhere and thus add to their income.

TABLE 6

## INDEBTEDNESS OF SETTLERS AT DURHAM STATE LAND SETTLEMENT WHEN CLASSIFIED BY SIZE OF ALLOTMENT AND DELINQUENCY, FEBRUARY 29, 1924

Size of allotment	Settlers not delinquent, unmatured indebtedness	Settlers delinquent	
		Unmatured indebtedness	Delinquent indebtedness
acres	dollars	dollars	dollars
0-2 99 . . . . .	10,372 50	4,692 02	332 89
3-14 99 . . . . .	18,692 47	7,306 03	875 54
15-29 99 . . . . .	35,536 95	81,625 37	15,277 04
30-64 99 . . . . .	57,985 28	207,166 62	31,222 60
65 or over . . . . .	14,655 59	149,756 44	25,803 54

## Source of data:

California Department of Finance, Division of Budgets and Accounts. [Report on the Durham State Land Settlement as of February 29, 1924.] (Typewritten.)

Table 7 shows the average delinquency and average semiannual payment due of delinquent settlers by size of allotment. The noticeable feature here is that the delinquency was usually three times the payment. Further detail on the amount of delinquency per farm is as follows:

Delinquencies	Number of farms with delinquencies
\$ 500-999 . . . . .	11
1,000-1,999 . . . . .	20
2,000-2,999 . . . . .	5
3,000 or over . . . . .	2

The evidence seems conclusive that a large number of settlers were not making good and that a large proportion of the state's assets were of questionable character.

The State Superintendent of Accounts, Mr. W. Schleip, had, however, a favorable impression of the settlement and summarized the situation as follows:

....the aggregate of original loans to settlers now transacting business with the State was \$859,661.15; deferred installments due State are \$587,879.29; payments due and delinquent are \$73,498.00 and the settlers equity in land and improvements acting as security for advances is \$198,283.86. This equity is further reduced by loans obtained from the Federal Farm Loan Bank at Berkeley secured by land and utilized to make payments to State in amount \$83,407.14. The net equity of \$114,876.72 is more than ample to secure the delinquencies. The State is further secured by the following facts, viz: 1. Loans on improvements were only 60 per cent of value of improvements. 2. An appraisal of unencumbered improvements owned by delinquent settlers values them at \$140,705.00 and the State could legally loan thereon sixty per cent of appraised value or \$84,423.00, or more than sufficient to wipe off the entire delinquency.<sup>101</sup>

<sup>101</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Durham State Land Settlement as of February 29, 1924.] (Typewritten.)

The valuations which were accepted by the auditor and which were those given in Mr. Kreutzer's appraisal were not, however, necessarily indicative of the real situation. For instance, the average valuation they accepted on 8 adobe farms was \$21,345.31 as compared with the average debt of \$13,622.84. Settlers' equities ranged from \$619 to \$15,251; yet the farms were so unproductive that the state had already arranged to take them back. Clearly the state was going to suffer a heavy loss on these farms. Similar evidence was available on at least one farm on the north side of the settlement which the Federal Land Bank had taken over to satisfy a mortgage. Subsequent production experience when viewed in the light of these debts, due and delinquent, demonstrated that the state was going to take a loss on virtually the entire settlement area.

TABLE 7

AVERAGE DELINQUENCY AND AVERAGE SEMIANNUAL PAYMENT DUE  
OF DELINQUENT SETTLERS AT DURHAM STATE LAND SETTLEMENT,  
CLASSIFIED BY SIZE OF ALLOTMENT, FEBRUARY 29, 1924

Size of allotment	Average delinquency	Average semianual payment due
acres	dollars	dollars
0- 2 99.	47 57	30 69
3-14 99..	291 85	113 89
15-29 99	954 85	240 07
30-64 99	1,040 75	327 79
65 or over	1,600 22	459 89

## Source of data:

California Department of Finance, Division of Budgets and Accounts  
[Report on the Durham State Land Settlement as of February 29, 1924.]  
(Typewritten.)

*Adequacy of Capital Supply at Durham.*—A liberal supply of capital was available at least to 1920, and there is no evidence of a shortage for any purpose thought to be needed by the Board through the next few years. Certainly a considerable number of settlers planted upwards of 500 acres of fruit trees and brought them into production. One definite need, that of improved drainage, did develop, however, and lack of funds may be regarded as a factor in the failure to carry out a large-scale program.

In an earlier section (p. 429), it was pointed out that funds apparently were provided at one time for drainage at Durham but were shifted to Delhi. Another reason for there being a lack of credit for a drainage system at Durham was that there was no agreement between the Board and the settlers as to who should ultimately pay for the cost of installing the system. Reports indicate that both wanted something done but neither would assume the cost. While the Board, probably at any time within five years of settlement, seems to have had authority to make improvements, no provision seems to have been made by which it could pay for any contingency such as the drainage system. The price which had been set had not been high enough to meet the requirements so that the money had to be obtained either from the Legislature or from the settlers with their consent. The latter was never given. The original intention was to have the settlers organize a mutual water company and thus accept

responsibility for operation of the irrigation system. This they refused to do, and no means were available to force them to comply. At the very first a settlers' committee had been established to manage the system. As time went on this committee accepted less and less responsibility. The years went by with a continual quarrel between the settlers and the administration regarding what should be done about drainage and who should pay for it. The little money that was spent seems to have been diverted from payments due the state. That there was no generally accepted determination of whether the state or the settlers should pay for improvements of this nature was, no doubt, an element in the failure to develop an adequate drainage system.<sup>102</sup>

<sup>102</sup> Some of the evidence of the intentions and powers of the Board is as follows:

"The board shall . . . lay out, and where necessary, construct roads, ditches, and drains for . . . insuring the proper cultivation of the several farms and allotments." Also: "The board, prior to disposing of it to settlers, or at any time after such land has been disposed of, but not after the end of the fifth year from the commencement of the term of the settler's purchase contract, may . . . make any . . . improvement . . . necessary to render the allotment habitable and productive in advance of or after settlement." (California Statutes, 1919, Chap. 450, Sec. 11.)

"The selling prices of the several allotments . . . shall be fixed by the board, . . . and calculated to return to the state the original cost of the land, together with a sufficient sum added thereto to cover all expenses and costs of surveying, improving, subdividing, and selling such lands, including the payment of interest, and all costs of engineering, superintendence, and administration, including the cost of operating any works built directly chargeable to such land, . . . and also such sum as shall be deemed necessary to meet unforeseen contingencies." (California Statutes, 1919, Chap. 450, Sec. 17.)

"Until a mutual water company has been organized and the settlers belonging to said mutual water company have assumed control of the irrigation system, the State Land Settlement Board will operate the irrigation works at the Durham State Land Settlement and levy an annual charge." (California State Land Settlement Board, Minutes of the California State Land Settlement Board, October 12, 1918. Typewritten; in files of California Department of Finance, Division of State Lands, Sacramento, California.)

"When 90% of the land has been disposed of to settlers, or earlier, at the option of the board, a mutual water company will be formed and shares of stock will be issued to settlers in proportion to the irrigable acreage of each allotment. The settlers, as owners of these shares, will operate the distribution system, beyond where water is taken from the canals of the Irrigation District, this system to include pumping plants and pipe lines. The actual cost of operating the mutual company will be borne by the settlers in proportion to the shares held, the cost of operating the pumping plants being made a part of the general expenses and spread over the entire area." (Notes by Dr. Mead on proposed publication: Farm allotments and farm laborers' allotments in the first and second units of Delhi State Land Settlement, September, 1920. Files of Giannini Foundation.)

"Up to the beginning of 1931 the irrigation system at Durham was operated by the State through a committee of settlers. The original plan of Land Settlement seems to have included no provisions for turning over the irrigation system to the settlers although evidence exists that such was the intention. By operating the system for a number of years, the State became obligated morally if not also legally to continue such operation until some individual or organization willing to assume this responsibility could be found.

"The year 1924 was one of deficient rainfall. Dissatisfaction resulted in connection with the operation of the irrigation system. The Land Settlement Board cooperated in drawing up By-laws for a Mutual Water Company but after a considerable amount of work had been done to organize such a company the opinion was given by the office of the Attorney General that under the Land Settlement Act, as it stood, such transfer could not legally be made. Nothing further came of this effort." (Bauer, O. W., Superintendent. Final report to Department of Agriculture Division of Land Settlement 1931. Typewritten; in files of California Department of Finance, Division of State Lands.) Also see: Mead, Elwood. Letter to Milo Williams. September 2, 1920. (Files of State Land Settlement Office, Delhi, California.)

### FINANCING AT DELHI

*Capital Supplied by Delhi Settlers.*—The most accurate information concerning the capital assets of Delhi settlers was obtained from the original application records of 258 settlers.<sup>103</sup> Unfortunately the records were not complete and many of those available were of settlers who soon left. Also, moves were frequent so that no acceptable classification could be made of the size of holdings. No check could be made of the money received from the sale of property owned outside the settlements. However, the information has some value. The 258 settlers had total book assets of \$1,065,100 at time of application. Approximately one third was in cash; one third was in land; and one third included automobiles, farm stock, machinery, bonds, cash value of life-insurance policies, notes, loans from relatives, estates in probate, and other similar items.

Assets other than cash were of doubtful value. While land was usually mentioned specifically and given a valuation, its realizable value was doubtful because the possibility of selling it at the price given was always open to question. Since land might be listed either at the owner's equity or with liabilities against it, even its book value was often unknown. If encumbered with mortgages, as was often the case, it might be a liability. Unless sold for cash to be used on the settlement, it would be of no assistance in any case. Other possessions such as farm equipment, livestock, and household furniture were of substantial importance to those people who owned them. To illustrate the questionable value of the property of many settlers, two extreme situations may be mentioned. One man listed assets of \$12,500, including \$6,400 in notes and \$3,000 in books. Since, however, he had \$2,800 in cash, he was among the strongest settlers. Another man listed assets of \$12,511, of which \$10,000 was land. He valued 1,000 chickens at \$2,000, his tractor at \$511. He had no cash and had liabilities of \$5,230.

Sixty-eight settlers had assets totaling less than \$1,500 each. On the average each had \$360 in cash. Most of this group moved onto laborers' allotments although a number later took larger allotments. Many who did this lacked the means to make any significant contribution toward developing a farm, unless they earned it after making their application.

In contrast, each of a group of 23 had over \$10,000 in total assets with an average of \$16,623. Their average amount of cash, however, was only \$2,591—not a considerable sum, since many of them purchased farms larger than the average. The main part of their assets was land; it averaged \$10,159 in stated value. These few men were credited with more than one third of the total assets brought in by settlers. The remaining settlers, having total assets between \$1,500 and \$10,000 and numbering 167, had average total assets of \$3,755, including \$1,551 in cash. If this group is combined with the richer group of 23 settlers, the average cash assets are \$1,677. This figure is probably typical of the group on the Delhi farms and poultry allotments and gives an average investment of about \$70 an acre.

As at Durham, one source of capital was money or credits earned after application for an allotment. Many worked for the settlement administration,

<sup>103</sup> Files of Giannini Foundation.

some worked for outside concerns, and a few went back to former jobs while their families remained on the allotment. The veterans, of course, had their income from the government. The number of people who thus added to their incomes is not known, but in every case investigated at Delhi in which the settler had a comfortable living while developing his farm, he received aid from one of these sources. Another important aid for a settler was the method by which he received credit for work he did on his own allotment. This was often regarded as work done for the state and the settler was credited accordingly.<sup>104</sup> This credit was then used as down payment for either the land or improvements. Building materials or other supplies were obtained on an accounts-receivable basis. While the settler was eventually charged for all items due the state, the initial financing was thus made easy. Just how frequently the procedure was required is impossible to discover, but it was evidently common.

These supplementary sources of income from jobs and credit for work on their own allotment are estimated to have raised the farmers' average capital contribution to \$100 an acre. The writer believes this figure is approximately correct.

The settlers, however, claimed that their investment was far greater than \$100 an acre, and in 1928 estimated that they had put \$900,000, or \$200 an acre, in money and \$1,500,000, or \$300 an acre, in labor into the settlement, making a total of \$500 an acre.<sup>105</sup> It is possible that the estimate of money was correct. The Board's report of September 1, 1922, states that the average capital of all 205 settlers then on the tract was \$3,251.<sup>106</sup> Those on farms would, of course, have had the larger share. Unfortunately, no details were given and it seems likely that this figure included not only cash but also property of doubtful realizable value.

By the end of 1924 the average debt of those on allotments of over 13 acres was \$354 per acre.<sup>107</sup> If the settlers' estimate of their equity of \$500 is accepted, the total investment in the Delhi farms as of that date was \$850 per acre. If the writer's estimate of \$100 per acre as the settlers' equity is accepted, the total investment was about \$450.

*Financial Developments.*—Although both the state and the settlers provided large sums of money, resort was made to other sources. Early in 1921 a number of settlers borrowed money from the First National Bank of Turlock with Mr. Packard, as Superintendent, guaranteeing the loans. The loans usually were for the purchase of cows; the bank could take chattels as security because the state did not have a prior claim as it did on land. The reason given in applying for a loan was that the settlers needed their money at once in order to pay for their purchase, but the administration, in making a loan, required considerable time before the money would arrive from Sacramento.<sup>108</sup>

<sup>104</sup> Packard, Walter E. Letter to F. A. Wilson, Felix, California. August 25, 1923. (Files of State Land Settlement Office, Delhi, California.)

<sup>105</sup> Batterman, W. S. [Speech at Delhi, November 9, 1928.] In: Settlers' executive meeting was held Friday night; propositions discussed. Delhi Record 5(41):4. November 16, 1928.

<sup>106</sup> California Department of Public Works, Division of Land Settlement. Report.... September 1, 1922. *op. cit.* p. 40.

<sup>107</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of December 31, 1924.] (Typewritten.)

<sup>108</sup> Packard, Walter E. Letter to L. T. Brown, First National Bank, Turlock, California. November 2, 1921. (Files of State Land Settlement Office, Delhi, California.)

Many loans, however, were not repaid immediately, and remained on the books for several years.<sup>169</sup> An interesting reason for encouraging these loans was given by Dr. Mead as follows: "I think the bank will press him harder to meet payments than we would."<sup>170</sup> The Board also made some effort to borrow from the War Finance Corporation<sup>171</sup> and the Joint Stock Land Bank.<sup>172</sup>

Loans from the Federal Land Bank were an important source of money at Delhi. They were made after the balance due Mr. Wilson had been paid off in the spring of 1922. Under the purchase contract he was to receive only part in cash and to hold a mortgage as security for the balance. In the spring of 1922 the Board offered to pay him the balance provided he would take back 361 acres of the poorest land at the purchase price.<sup>173</sup> He agreed, and in this way they disposed of some very poor land. Another reason for the deal was to obtain more money for development.<sup>174</sup> The general aspects of the plan were as follows: By eliminating the Wilson mortgage and by giving each settler a deed to his land to replace his purchase contract, the Board made it possible for the settlers to give a first mortgage to the bank. The state would hold a second deed of trust for its own investment.<sup>175</sup> The Board hoped that they would be able to borrow some \$500,000 in this way.<sup>176</sup> Since the net amount due Mr. Wilson was about \$260,000 this would give the Board about \$240,000 to use for development. The organization of a farm-loan association was begun in March, 1922.<sup>177</sup>

The Federal Land Bank evidently did not consider these loans as an ordinary type. The officers gave great weight to the fact that the state had initiated the settlements, had set up a permanent supervisory administration, and would be the holder of junior obligations of the settlers.<sup>178</sup>

Moreover, the settlers did not like to have these loans made. For one thing the bank charged them 5½ per cent for its money while the state charged only 5 per cent.<sup>179</sup> Also, they were given a deed to their land in order that the bank

<sup>169</sup> Whipple, F. B., First National Bank, Turlock, California. Letter to J. Winter Smith. June 9, 1925. (Files of State Land Settlement Office, Delhi, California.)

<sup>170</sup> Mead, Elwood. Letter to Walter E. Packard. March 16, 1922. (Files of State Land Settlement Office, Delhi, California.)

<sup>171</sup> Packard, Walter E. Letter to Elwood Mead. February 22, 1922. (Files of State Land Settlement Office, Delhi, California.)

<sup>172</sup> Mead, Elwood. Letter to A. B. Fletcher, Director of Public Works, Sacramento, California. July 24, 1922. (Files of Giannini Foundation.)

<sup>173</sup> Mead, Elwood. Letter to Mortimer Fleishhacker. April 3, 1922. (Files of Giannini Foundation.)

<sup>174</sup> Smith, J. Winter. [Report to California Department of Agriculture, Division of Land Settlement. July 29, 1927.] (Typewritten; in files of California Department of Finance, Division of State Lands.)

<sup>175</sup> Packard, Walter E. Letter to Elwood Mead. February 18, 1922. (Files of State Land Settlement Office, Delhi, California.)

<sup>176</sup> Mead, Elwood. Letter to R. T. Evans, Treasurer, Federal Land Bank, Berkeley, California. April 3, 1922. (Files of Giannini Foundation.)

<sup>177</sup> Packard, Walter E. Letter to Elwood Mead. March 15, 1922. (Files of State Land Settlement Office, Delhi, California.)

<sup>178</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of August 13, 1931.] (Typewritten; see statement of F. M. Hannon, Auditor.)

Packard, Walter E. Letter to Frank English, Deputy Attorney General, San Francisco, California. September 25, 1922. (Files of Giannini Foundation.)

<sup>179</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of December 31, 1924.] (Typewritten.)

Smith, J. Winter. [Report to California Department of Agriculture, Division of Land Settlement. July 29, 1927.] (Typewritten; in files of California Department of Finance, Division of State Lands.)

loan could be made, and thus their property was taxable, which was not the case when the state held title. Consequently, some settlers not only paid a higher interest rate than others but also paid land taxes, while the others were exempt. No little ill feeling was aroused over this situation. In fact, some settlers refused to apply for a Land Bank loan unless they were granted an additional loan by the state.

After the final payment to Mr. Wilson in March, 1922, and before any money was obtained from the Federal Land Bank, the settlement office had about \$135,000 available from the 1921 legislative appropriation. This was expected to last until about July 1, 1922.<sup>120</sup>

The administration estimated their needs for all development and loans after that date at about \$650,000.<sup>121</sup> They still had all development work to do on the fourth, or Ballico, unit, which included 8 laborers' allotments and 97 farms. They had upwards of 45 allotments unsold on the other units. Only a half dozen of these were laborers' allotments; most would require loans of considerable amount. (See p. 452.) The Board wanted some \$200,000 from the bank between July 1 and December 31, 1922, but by the latter date only \$110,011.01 had been received. Even with a temporary loan of \$20,000 by the State Board of Control the total was short of their needs.<sup>122</sup> The loans from the Federal Land Bank continued to be slow and the shortage rapidly grew more acute. On February 24, 1923, Mr. Packard described the situation as follows: "We have no funds in the treasury at all now, and claims are in Sacramento being held."<sup>123</sup>

On May 17, 1923, there was practically no cash, and unpaid bills totaling \$73,458.11 were on file.<sup>124</sup> In July, when loans had reached a total of \$305,100, the bank stopped making more. The only exceptions were two which were made in 1924 and which were probably approved because of the security offered by the individual borrowers. One can only guess at the bank's reasons for stopping these loans, but probably the delinquencies and changes in state-administration policies had much to do with it. Dr. Mead was away at the time. Mr. Packard states that the bank officials promised to consider more loans on Dr. Mead's return but nothing was done.

Meanwhile with the November, 1922, election came the defeat of the \$3,000,000 bond issue, which had been proposed by the 1921 Legislature and which had come close to being approved in the general election. Little campaigning had been done for or against the issue; but the general economy campaign of Friend W. Richardson, who was elected Governor, a strong campaign against some state public-utility-bond issues, and interest in a bond issue for an ex-servicemen's farm-and-home-purchase plan, combined to defeat the measure. As for legislative appropriations, Dr. Mead stated shortly

<sup>120</sup> Mead, Elwood. Letter to Mortimer Fleishhacker. April 3, 1922. (Files of Giannini Foundation.)

<sup>121</sup> Mead, Elwood. Letter to R. T. Evans, Treasurer, Federal Land Bank, Berkely, California. April 3, 1922. (Files of Giannini Foundation.)

<sup>122</sup> California State Board of Control. Emergency Resolution No. 22. August 2, 1922. (Files of Giannini Foundation.)

<sup>123</sup> Packard, Walter E. Letter to Elwood Mead. February 24, 1923. (Files of Giannini Foundation.)

<sup>124</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of May 17, 1923.] (Typewritten.)

after the election that he expected no help from the Legislature in the coming session.<sup>185</sup>

A review of the 1922-23 winter construction period shows that the Division of Land Settlement obtained funds for only about half of the planned expenditures. During the same period the settlement administration lost its political support and realized that no new financial help could be expected from the Legislature for two years. The Federal Land Bank stopped all loans in July, 1923.

The State Land Settlement Office was supposed to have an income from interest and amortization payments but the settlers did not keep up their payments. According to the auditors' report, the amount due and delinquent from settlers on December 31, 1922, was \$73,445.27 and amounts due on open account \$49,150.11. Of the 239 land contracts, 222 were delinquent; of the 142 improvement contracts, 122 were delinquent; and there were accounts receivable from 205 settlers. The auditor commented as follows in regard to the situation :

A survey should be made with a view to determining the condition of affairs of each settler, his ability to make payments, the value of his allotment, whether properly developed and cared for, etc. This has not been done in the past.....

Greater effort should be made to collect from settlers.....

Appraisals should be made periodically of property under chattel mortgage to the settlement. This has not been done in the past.....

We respectfully recommend that a thorough investigation be made of the value of State Land Settlement as exemplified at Delhi, both from the viewpoint of the State of California and the present and prospective settlers.<sup>186</sup>

Conditions rapidly grew worse during 1923. By December 31 the amount due and delinquent from settlers was \$128,157.11 and the amount due on open account was \$58,662.94. Current liabilities were \$26,773.66 and available cash was \$7,651.53.<sup>187</sup> Settlers and administration alike became thoroughly demoralized. The following descriptions by one of the engineers under Dr. Mead of the situation in the spring of 1924 are believed to be accurate.

95% of the settlers are delinquent in their payments.

. . . . . Forty-eight land bank payments fall due today. Half of these cannot be met by individuals.....

. . . . . There is less than \$3,000.00 on hand with practically no income, and the prospect of realizing on collection very poor.

. . . . . Collateral sold without our permission or previous knowledge.....

. . . . . There is but one single outstanding instance where chattels are protected by insurance. ....

. . . . . 40 absentee settlers with building development in which State holds interest being neglected.....

. . . . . 27 of these developed allotments are wholly unoccupied with alarming depreciation.<sup>188</sup>

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<sup>185</sup> Mead, Elwood. Letter to Walter E. Packard. February 28, 1923. (Files of Giannini Foundation.)

<sup>186</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of December 31, 1922.] (Typewritten.)

<sup>187</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of December 31, 1923.] (Typewritten.)

<sup>188</sup> Cook, Max, Farmstead Engineer. Existing conditions Delhi administrative affairs, April 1, 1924. (Typewritten; in files of State Land Settlement Office. Delhi, California.)

Mr. Wooster, who succeeded Dr. Mead as chairman of the Board, made the following statement:

The original plan provided for the loaning of the State's money to settlers, secured by chattel mortgages, and 136 of such loans were made prior to 1924. Such loans run from three to five years with interest at 5%. Practically none of these obligations were paid. In most cases the security, consisting of hogs, chickens, horses, cows or implements, was sold, lost, destroyed or otherwise dissipated and no substitutions were made therefor. A check in 1924 developed that the security was much less than the amount owing the State. Collection by means of mortgaged security was impossible.<sup>159</sup>

Funds were so short that spring that a complete shutdown of operations was threatened. The Board of Control was asked for an emergency loan but Governor Richardson at first refused to allow it; he felt the state was not justified in adding more money to that already lost. Only by an appeal on humanitarian grounds could he be persuaded to allow a \$40,000 loan.<sup>160</sup> This, with loans from banks, permitted the settlement organization to operate until the Legislature met the following year. At that time \$250,000 was appropriated<sup>161</sup> to finish needed construction, provide for operating expense, pay Board of Control loans, and make additional loans up to \$50,000.<sup>162</sup>

*Reasons for Shortage of Funds at Delhi.*—It is evident that there was a severe shortage of capital at Delhi. The reasons for this shortage are four in number. The original and most important reason was the inadequate surveys and estimates of cost. The only record found of such estimates were those which related to the irrigation system and which have been discussed (p. 411). The engineers who made them, considered them inadequate at the time. Since estimates were inadequate the Board naturally failed to arrange for the proper amount of funds. Certainly the Board did not anticipate the expenditures required.<sup>163</sup> It might be reiterated that price changes in construction costs were favorable. (See p. 440-42.)

The second reason for a shortage of funds was the failure of the various sources to provide as much money as was wanted. The sources, however, cannot be held responsible for this situation. All the evidence indicates that the Legislature in 1917, 1919, and 1921 appropriated all the funds which the Board thought it would need. The bond issues could hardly have been depended on until they were approved. In particular, the Board knew at the time of the 1921 appropriation that no bond issues would be likely to be voted on until November, 1922. The Federal Land Bank also was not depended on originally at Delhi, otherwise the Board would have given the settlers deeds to their land rather than contracts of purchase. Considering the character of the land purchased, the sums made available seem to have been liberal.

The third reason for the lack was the nature of the crops planted; peaches, grapes, alfalfa, and dairies require heavy initial investments. Moreover, no important returns could be expected from peaches for about five years, from grapes for three years, and from alfalfa for one year. A dairy might bring

<sup>159</sup> Wooster, C. M. [Report to Governor Richardson.] December 31, 1925. (Typewritten; in files of C. M. Wooster.)

<sup>160</sup> Smith, J. Winter. Interview, July, 1939.

<sup>161</sup> California Statutes, 1925, Chap. 205.

<sup>162</sup> California Department of Agriculture, Division of Land Settlement. Final Report. June 30, 1931. p. 28. Sacramento. 1931.

<sup>163</sup> See correspondence between the Berkeley, Delhi, and Sacramento offices.

immediate returns if the initial investment were heavy, but if this were kept down the returns might be considerably reduced by the need to expand. Annual crops, while frequently tried, brought such poor returns that they were considered a last resort. With low or no returns to be expected during the first years, the settlers required other financial assistance.

The fourth reason for the lack of funds was the poor crops. They discouraged additional settlers and reduced the loans made by banks. In the long run the poor yields prevented the settlers from obtaining a good income and thus from building up their allotments with that source.

*Effect of Shortage of Funds on Development of Farms for Sale.*—Construction and development came to a stop because of the shortage of funds. But from the standpoint of success of the settlements, this fact is of no importance. As shown in the discussion on selling land (p 421-23), there were always farms for sale in the settlement. The failure to sell the land cannot be ascribed to lack of capital. Rather it was due to the national economic situation and to the production situation on the settlements. Sales came to a stop before funds ran out. The preparation of more land for sale would have been to no purpose.

*Effect of Inadequacy of Funds on the Development of Farms Sold.*—The statement is frequently made that the settlers failed for lack of capital to develop their farms. The most important evidence on this matter is the development which took place. In 1925 there were 2,400 acres of alfalfa; 1,200 acres of trees, well on the way to maturity; 600 acres of vines, mostly mature; and 800 head of cows and heifers on the settlement. This development would not have been possible if considerable capital had not been available. Further evidence is the fact that the settlers borrowed enough to make their debts average \$354 an acre by the end of 1924 and invested \$100 an acre of their own money. From what can be learned these amounts were enough to bring most places into production. This does not mean the settlers could withstand crop losses.

Some of the last settlers to purchase may have lacked funds. Reliable evidence has been found that this was true of a number who wanted to expand their dairies. In view of the credit obtainable from local banks, these cases cannot be regarded as very numerous. Mr. Packard, on February 28, 1923, stated: "We are taking a large number of people without funds enough to develop unless the State can continue to make loans."<sup>104</sup>

It may be pointed out, however, that settlers by that time had ceased to come; in fact not more than 30 had arrived during the preceding six months. (See p. 422.) Since the policy of the Board had been to get every farm into full production, and since all information indicated that this was fully carried out, there is good reason to believe that earlier settlers had progressed far enough by 1923 to keep going without any particularly large new loans.

At the time of his final report, February 8, 1924, Mr. Packard stated that: "Forty settlers have applications on file for loans."<sup>105</sup>

On May 1 of the same year Mr. Cook stated: ". . . there are applications for loans on file for between \$20,000.00 and \$25,000.00. They are all urgent."<sup>106</sup>

<sup>104</sup> Packard, Walter E. Letter to Elwood Mead. February 24, 1923. (Files of Giannini Foundation.)

<sup>105</sup> Packard, Walter E. [Report . . . February 8, 1924.] *op. cit.*

<sup>106</sup> Cook, Max. Existing conditions Delhi administrative affairs, April 1, 1924. (Type-written; in files of State Land Settlement Office, Delhi, California.)

According to Captain J. Winter Smith, who became superintendent at that time, the Board of Control loan of \$40,000 was designed to take care of these cases. That this was very nearly sufficient was indicated by a statement by Mr. Packard in his final report.

If an advance of \$50,000 could be made by the Board of Control, our difficulties would be at an end . . . . The income from settlers should certainly be sufficient to keep up all administration costs and loans to settlers.<sup>197</sup>

It seems likely that Mr. Packard referred here only to those settlers already established on the settlement. The general indication is that most of the settlers who needed to borrow money for development during these years were able to obtain considerable amounts.

It must also be pointed out that the settlers at Delhi were spared some important cash expenditures during these years. No taxes were paid on land owned by the state, and all sales made by contracts of purchase left the title residing in the state. This was true for everyone until 1923 when those who had borrowed from the Federal Land Bank, and had been given deeds in order to do so, had to pay taxes. These were smaller, however, than those paid by others in the community because the California Supreme Court held that taxes could be levied only on each settler's possessory right or equity.<sup>198</sup> This reduction amounted to 48 per cent in 1926.<sup>199</sup> All veterans in California were exempt on the first \$1,000 assessed valuation of property. This often meant complete exemption.<sup>200</sup>

Of far greater importance than these tax exemptions was the fact that the state did not force the settlers to meet their payments. This left such income as was obtained to be used for going expenses, living, or development. Such payments as were made to the State Land Settlement Office were in part used for new loans. Mr. Packard reported that up to the time he left, "No interest . . . [had] been paid to the state. . . . the money having been used in lieu of an added appropriation."<sup>201</sup> By 1925 this amounted to \$350,000.<sup>202</sup> Other than the payments made to the Federal Land Bank and private banks, the settlement as a whole made no interest payments for all the money it borrowed.<sup>203</sup>

In view of the development that actually took place, the amounts invested, and the low payments made for taxes, interest, and amortization, the conclusion is reached that most of the settlers had sufficient capital to develop their farms properly.

*Effect of Shortage of Capital on Morale.*—The failure of the State Land Settlement Office to obtain larger amounts of capital for construction work and loans must be regarded as an important cause for the break in morale at Delhi in 1923. A large number of the settlers had literally lived off their construction jobs or their loans. With these gone they lost a principal source of

<sup>197</sup> Packard, Walter E. [Report . . . February 8, 1924.] *op. cit.*

<sup>198</sup> State Land Settlement Board v. Henderson. (1925) 197 Cal. 470.

<sup>199</sup> Smith, J. Winter. General review of tax situation. *Delhi Record* 4(9):1. April 8, 1927.  
<sup>200</sup> Wooster, C. M. [Report to Governor Richardson.] December 31, 1925. (Typewritten; in files of C. M. Wooster.)

<sup>201</sup> Packard, Walter E. [Report . . . February 8, 1924.] *op. cit.*

<sup>202</sup> California Statutes, 1925. Chap. 302. (Act remitting interest charged against State Land Settlement Fund.)

<sup>203</sup> California Statutes, 1931. Chap. 153. (Act remitting interest charged against State Land Settlement Fund.)

income. With farms producing poorly or not at all, many were in serious difficulties. Some had to go elsewhere to seek a living, all had to restrict expenditures. This situation, however, must not be regarded as indicating that funds were inadequate for development of their allotments; rather it shows the poor farm income received by all settlers, established or new—an income which would not have been corrected by more loans.

### REORGANIZATION AT DELHI

It seems clear that the settlers at both Delhi and Durham encountered difficulties so serious that success was very remote. These difficulties have been described, and while many more details might be added, it is believed that a comprehensive picture has been given. From the viewpoint of causes of failure there is little more to tell.

The problem now to be dealt with is that of who would bear the losses that were being incurred. This distinction of causes of failure from distribution of losses is designed: partly to emphasize that the losses at Delhi and Durham were due to physical and economic factors, largely beyond the power of the people concerned to correct; and partly to separate the factors which caused failure from the factors which influenced the distribution of losses. This separation is justified because the disputes that arose between various persons and groups, while including many allegations concerning the causes of failure, were important only as they affected their respective financial standings. From a social viewpoint, it is apparent that since the crops were not productive and since capital and effort could never find recompense, society stood to lose, regardless of which groups or individuals bore the burden and which went free. Success here refers to the settlement projects as a whole, not to any particular individuals or groups.

In discussing the disputes that arose between these individuals and groups, it must be emphasized that during the early years, the settlers displayed exemplary qualities; they worked hard, coöperated, and maintained a confident spirit. As difficulties multiplied, however, they became disappointed, then antagonistic, and finally wholly bent on forcing the state to rectify their "wrongs." This change of attitude, it must be understood, followed the discovery that returns were not going to be satisfactory. Production and economic difficulties occurred regardless of settler attitude and were causal factors; settler opposition was a result.

*The Development of Settler Discontent at Delhi.*—The first sign of organized discontent among the settlers appeared in the summer of 1922. A newly installed American Legion Post, in a report on the local situation, made a number of suggestions, among them the following:

If the legislature would amend the land settlement act, so that the settlers were given a longer time in which to get started without having to meet other than the initial payment, the project would be developed to the satisfaction of all financially.<sup>24</sup>

In answer to this Mr. Packard wrote a letter to the Post Commander:

I am sure that you realize that the State could not enter an arrangement which would be unsafe from a financial standpoint, and that any modification made in the Act referring to

<sup>24</sup> Packard, Walter E. Letter to Post Commander, Delhi Post American Legion. August 17, 1922. [Contains excerpts from report.] (Files of State Land Settlement Office, Delhi, California.)

postponement of payments must conform to sound business practice. With this in mind, I feel that a public statement regarding changes in the Act relating to change in the payment plan, should either be withheld until the matter had been considered seriously by the legion after a careful investigation, or should be so put as to express an impression, which would be considered on its merits later.<sup>205</sup>

The report of the Post also declared :

It was the general concensus of opinion that a number of changes should be made in the contracts, policies of the Land Settlement Board, and the Land Settlement Act, for the benefit of the Settlement.<sup>206</sup>

Mr. Packard's answer was as follows :

I do not wish to convey the idea that criticism is not desirable or needed, but it seems to me a public statement that a number of changes should be made in the contracts and policies of the Division of Land Settlement, and in the Act, should not be made before the questions involved have been carefully weighed by the Legion with a full presentation of all angles of the problem, and with a formal studied vote by the Legion after a report had been submitted by a committee of investigation. A hasty public statement may be misleading, and may cause misunderstanding and result in trouble.<sup>207</sup>

From this early encounter, one or two important particulars can be gathered. Some of the settlers were making objections, especially about the difficulty of meeting payments. The settlement officials were well aware of this situation and, while avoiding a public dispute, asked for an investigation. They handled the problem so that no serious trouble grew out of it; the Post did not even make the investigation. In fact the Veterans Bureau was trying at this very time to send some of its men to Delhi and did settle some there later in the fall. Shortly before, moreover, on July 26, 1922, Mr. Elmer L. Sherrell, Chief of the Rehabilitation Division of the United States Veterans Bureau at San Francisco, stated in a letter to local supervisors: "The group of men who are now at Delhi we believe are well cared for and we cannot speak too highly of the project as it now stands."<sup>208</sup>

Difficulties rapidly developed, however, between the Veterans Bureau and the State Land Settlement Office. The trainees were not satisfied with their prospects. Early in 1923 Major Louis T. Grant of the Bureau told Dr. Mead in a conference that he no longer believed the trainees could succeed at Delhi and that withdrawal would be necessary. Later in April, Mr. Packard wrote Dr. Mead that the agreement with the Bureau should not be continued.<sup>209</sup>

Early in 1923 the settlers presented what was apparently their first general demand for financial relief. The request was made by the directors of the Delhi Coöperative, representing, one may assume, a considerable proportion of the settlers. At the meeting the committee asked Dr. Mead to replace their delinquencies with short-term notes so that they would not be in a position to be foreclosed against at any time. This request was refused.

Shortly after this Dr. Mead left for Australia. He had been invited to conduct an investigation for the governments there. Later he visited Palestine and other countries and did not return until the end of the year. During his absence Mr. Kreutzer served in his place.

The next move of the settlers was to form a Settlers' Welfare League. Some

<sup>205</sup> *Ibid.*

<sup>206</sup> *Ibid.*

<sup>207</sup> *Ibid.*

<sup>208</sup> Sherrell, E. L. Circular letter. July 26, 1922. (Files of Giannini Foundation.)

<sup>209</sup> Packard, Walter E. Letter to Elwood Mead. April 4, 1923. (Files of Giannini Foundation.)

of the more discontented were elected officers. At a mass meeting in June the League adopted the following resolutions:

1. That money from federal loans should be applied on delinquencies which may occur.
2. That payments on the property be based on average crop production.
3. That the limit of borrowing be increased from \$3,000 to \$5,000.
4. That the present general committee for the settlers be made permanent.
5. That a court of appeals with powers of arbitration be created to handle settlers' problems.
6. That payments in excess of the semiannual payments may be applied to succeeding payments.
7. That the settlers support and coöperate with the present Land Settlement Board.<sup>210</sup>

These ideas involved some important changes in the relations between the settlers and the Board. Although the State Land Settlement Office had made clear that Federal Land Bank loans were to replace a part of the state loans, many settlers argued that they should be used to cover delinquencies. The crop payments would have involved a complete new contract and the assumption of much more risk by the state. The proposition that a court of appeals be set up was pushed and caused some anxiety to settlers who had not joined the movement and who did not wish any group to have the right to study their relations with the office.<sup>211</sup>

Late in July the officers of the San Francisco office of the Veterans Bureau appointed a commission to investigate conditions at Delhi. The commission came to the colony, established themselves in a garage without notifying the State Land Settlement Office of their intentions, and proceeded to hear testimony. According to available reports, the witnesses were very critical of the settlement administration. The committee drew up a report and presented it to Governor Richardson.<sup>212</sup> He gave it to Mr. Packard and asked him for his comments.<sup>213</sup> While the investigation led to no tangible results, it seemed to let loose a flood of discontent. From then on, the dissatisfied felt free to express themselves; more and more of the settlers became outspoken in their antagonism.

*Administrative Reorganization.*—Shortly after the investigation by the Veterans Bureau the settlers asked for a hearing before Governor Richardson. At first he avoided seeing them, evidently relying on the settlement officials, but by persistence they won his attention. He then appointed Mr. C. M. Wooster to a vacancy on the Board and turned the problem over to him.

When Governor Richardson started his term in January, 1923, he paid no attention to the land-settlement activity and left the entire administrative force in office. Also he approved all administrative changes in the law that Dr. Mead desired, including the abolition of the Division of Land Settlement and the restoration of the State Land Settlement Board as an independent organ-

<sup>210</sup> Sacramento Bee, June 23, 1922. (News article.)

<sup>211</sup> Packard, Walter E. [Report . . . February 8, 1924.] *op. cit.*

<sup>212</sup> The writer has not been able to obtain a copy of this report. However, see, "Record of a conference held at Delhi, California, on July 26th, 1923, between Walter Packard, Superintendent of the Division of Land Settlement at Delhi, and members of a commission detailed by Major L. T. Grant, Director of the 12th District of the United States Veterans Bureau to investigate conditions surrounding trainees of the Veterans Bureau located in this district." (Files of Giannini Foundation.)

<sup>213</sup> Packard, Walter E. [Letter containing "reply to the findings of the commission" to Governor F. W. Richardson.] October 20, 1923. (Files of Giannini Foundation.)

ization.<sup>214</sup> If the Governor had intended to have any direct influence over the settlement activity, he would probably not have done this.

Under the former arrangement, important matters had to be approved by the Director of the Department of Public Works.<sup>215</sup> Under the new arrangement Dr. Mead's approval was final. The Board constituted as in 1920, resumed its old functions. One vacancy existed, but Governor Richardson did not fill it until forced by the settlers to take action. His only adverse position was in regard to appropriations. Having won his election on an economy platform, he made many cuts in regular appropriations and would no doubt have vetoed further capital expenditures in land settlement if such a bill had been presented to him. Throughout most of 1923 he gave every support to Mr. Packard, particularly at the time of Veterans Bureau investigation. Though his whole political philosophy was doubtless opposed to the state land-settlement activity, he gave it no particular attention until after discontent and agitation satisfied him that some action was necessary.<sup>216</sup>

Mr. Wooster, the new board member, was a veteran real-estate operator and had an intimate knowledge of private land settlements. He had previously opposed state land-settlement activity and predicted the failure of Delhi.<sup>217</sup> Concerning his first visit to Delhi, however, Mr. Packard wrote to Dr. Mead:

Mr. Wooster was here last week and after a careful inspection of the settlement and an interview with a dozen or more settlers, he was very much impressed with the development and very much pleased at the progress that had been made. He said that it was very much better than he had anticipated and that there was no question but that settlers here would succeed if they would do the necessary work in the development of their allotments. I am sure he will have a helpful attitude for he certainly had this attitude on the day that he visited here.<sup>218</sup>

While this statement indicates that some coöperation might have been expected among the administration members, the actuality was quite the opposite. Innumerable differences developed. While Mr. Packard was well aware of the problems involved, he had only a subordinate position, he had already lost the confidence of many settlers, and soon realized he had no support from his superiors. Dr. Mead was away. Mr. Kreutzer seemed unable to suggest any suitable action. Mr. Wooster had the confidence of the Governor and was looked to by the settlers as one who might help them, but he was only a board member and had no authority. Although matters rapidly grew worse no action was taken which might have alleviated the situation. Mr. Packard, however, maintained a spirit of confidence. His viewpoint was well expressed in a report to Dr. Mead on December 31, 1923. After reviewing the situation on construction, land sales, and finances, he continued as follows:

All of the outstanding bills will be paid by the last of January, provided our affairs proceed normally. This seems to be a creditable showing for a period admitted to be the most difficult period in any project, particularly when the settlement was being maliciously attacked from both within and without.

<sup>214</sup> California Statutes, 1923, Chap. 411.

<sup>215</sup> The director, Mr. Fletcher, seems to have followed Dr. Mead's judgment, but the technical requirement was often irritating. (Correspondence in files of Giannini Foundation.)

<sup>216</sup> Richardson, F. W. [Speech at Delhi, June 16, 1925.] In: Mass meeting celebration. Delhi Record 2(19):1. June 18, 1925.

<sup>217</sup> Wooster, C. M. Letter, April 6, 1922. (Files of Giannini Foundation.)

<sup>218</sup> Packard, Walter E. Letter to Elwood Mead. November 5, 1923. (Files of Giannini Foundation.)

If the Land Bank will make further loans, as I am told they will after your return, we can proceed without further financial embarrassment as the 8,000 acres of land are paid for, the irrigation system—costing \$500,000—is paid for and operating satisfactorily, the State holds contracts and accounts due and protected by sufficient margin, totaling over \$1,300,000, in addition to land, buildings and equipment valued at over \$1,000,000, leaving a safety margin, of approximately \$250,000 as a protection to the State's investment.

The officers of the Welfare League have so demoralized the morale of the community that it will take vigorous action on the part of the administration to recover the spirit that formerly existed and which has been the motive force behind the development of the colony up to the present time. These men have constantly visited settlers and tried to discourage them, and have advertised the fact as widely as they could that settlers, were, in their opinion, not making it. It happens that all the officers of the League are men who came here with money and three officers have received over \$5,000 from the state.

The claim is made that men have been allowed to come to Delhi without sufficient funds. Facts show, after analysis of financial statement, that in many cases the settler who came here with the least amount of money has made the most progress and has increased his assets materially during the past two or three years. In my opinion, 85 per cent of the settlers will succeed if the unfair and untrue attacks made by those men are stopped.

I believe that it was a mistake to postpone the foreclosure in Mr. [———'s] case as I feel that some demonstration of this kind is necessary in order to make the agitators realize that they have entered into a business contract with the State of California and must meet the terms of that contract.

Suggestions have been made that some of the service rendered by the State should be dispensed with. An analysis of the cost of all service rendered settlers, less the charges made for this service, shows a total of approximately \$3. per acre. When the State has two million dollars involved in a project such as this, it is certainly good business practice to protect the State's margin by a service which makes for success. This service, of course, will be reduced as the need for it vanishes....

I feel that it would be a calamity to allow the Settlement to drift into an indifferent development where the State would lose and where the settlers would not realize the success which they can reasonably anticipate.<sup>219</sup>

Dr. Mead returned about this time and immediately decided that foreclosure was necessary. This the Governor would not permit. His statement follows:

On Mead's return I asked for his opinion and he denounced most of the colonists as anarchists and recommended foreclosure and ouster. He told how he had proceeded against the colonists in Australia, levying on their stock and goods and forcing them out penniless and shorn. I told him firmly that such inhuman procedure would not be tolerated by me in California.<sup>220</sup>

The Governor then appointed Mr. Wooster as chairman of the Board but asked Dr. Mead to serve as a member. This Dr. Mead refused to do, stating that he would be unable to work with Mr. Wooster.<sup>221</sup> Governor Richardson replied, in part, as follows:

I do not believe in the policy of foreclosure and think these settlers must be dealt with gently. It certainly should be done in view of the fact that conditions were badly misrepresented to them in the first place, and that the management of the settlement has been conducted very inefficiently.

I had hoped that you would stay with the board and lend your services to the solution of this very difficult problem.<sup>222</sup>

<sup>219</sup> Packard, Walter E. Letter to Elwood Mead. December 31, 1923. (Files of State Land Settlement Office, Delhi, California.)

<sup>220</sup> Richardson, F. W. [Speech at Delhi, June 16, 1925.] In: Mass meeting celebration. Delhi Record 2(19):1. June 18, 1925.

<sup>221</sup> Mead, Elwood. Letter to F. W. Richardson. January 26, 1924. (Files of Giannini Foundation.)

<sup>222</sup> Richardson, F. W. Letter to Elwood Mead. January 30, 1924. (Files of Giannini Foundation.)

Dr. Mead, by this time, had lost all influence with the settlers. Their extreme antagonism was shown shortly afterward when a group of men broke into Community Hall, cut a painting of Dr. Mead from its frame, and hung it in effigy above the road.

Mr. Packard resigned as superintendent in February and Captain J. Winter Smith was appointed to succeed him. He had had some experience in similar work and was well recommended. Mr. Kreutzer, at Durham, resigned that summer and was succeeded in time by the secretary of the Board, Miss Margaret Marshall.

*The 1925 Adjustment.*—Almost from the first, the Settlement Board under Mr. Wooster was committed to adjustment. That the Governor should favor a reduction in prices for settler farms was indicated by his statement on misrepresentation. To acquaint the Legislature with the situation, a committee of investigation was appointed early in 1925. After a visit to the colony, it reported as follows:

That the amount required each year to meet payments to the State, taxes, irrigation taxes and irrigation maintenance is about \$33.49 per acre.

That a great part of the acreage has been planted to fruit, which will not produce for several years. That 38% of the farms have produced no income to date, and for those that have, the average has been \$451.20 per farm or an average of about \$17 an acre.

.... The loans promised to settlers for use on their farms have not been made in many instances

The project as a whole has been, and now is, a financial failure. The settlers were led to expect too much; ....

In a number of instances chattel mortgages were made by settlers to the Board securing loans made by the Board. Later the mortgaged chattels were sold by the mortgagors and the loans were not repaid to the Board.

Furthermore, in addition to the general expectation of more help than is economically sound or larger loans than was financially or legally proper, many of the settlers came to the colony with the distinct belief that the State would act as a sort of guardian angel or Santa Claus and "see them through" as they expressed it.

The final consideration of this problem has led your committee to recommend that the State of California should never enter into another land settlement scheme.<sup>22</sup>

The views of the settlers are shown in an editorial in the *Delhi Record*, written by one of the settlers:

We had hopes, up to a few years ago, that the Delhi Cross Word Puzzle might be solved without needless and damaging publicity. And such would have been the case had those in charge of the project displayed even ordinary foresight. Any settler possessed of the average intelligence and a smattering of horse sense could and did see just a few months after the settlement got under way, to a start, as auspicious as any settlement could reasonably hope for, that the Mead plan would not answer here. Instead of immediately getting to the bottom of the trouble finding and eliminating the weak links, the father of the project permitted matters to take their natural course with the result that the sign "Bankrupt" might just as well have been placed over the entrance to the Land Settlement office and on the homes of most of the settlers. From the beginning it became apparent that settlers could not meet their payments. Then was the time to change the plan; to get the proper shoe to fit the foot or, to abandon the project. Definite action at that time would have eliminated all this useless publicity which has [hurt] and is hurting California.

<sup>22</sup> California Legislature. [Joint Legislative Committee Investigating State Land Settlement at Delhi.] Report of Joint Committee, Journal of the Senate during the forty-sixth session of the Legislature of the State of California, 1925, p. 629-30, 1925. (The writer has never been able to find a stenographic record of this investigation, although the legislature ordered that a copy be filed in the archives.)

Instead, a course of subterfuge; of evasion; of rosy promises and glowing messages to the press was adopted. The growl they claim came only from disgruntled types that could not succeed anywhere. In fact, it was as much as your investment here was worth to mention things publicly or attempt a little sincere and well-meant criticism. Just what those in charge hoped to accomplish by such a course has always been a puzzle to us.

We have been equally puzzled to learn why the acreage here was purchased at peak prices. Certainly, there was no real need of rushing the thing thru. And, as we get it, the original idea was to people the project with ex-service men. Just as soon as the idea was sold to the legislature and, the flag waving dispensed with, the soldier plan was dropped. Not so long ago, Dr. Mead attempted to place the blame for the Colony's trouble on the ex-service men here. As a matter of fact, disabled veterans have paid more man for man into the project than the civilian settler. Many here have received vocational training and compensation thru the Veteran's Bureau and the State has profited thereby.

Any business man knows that it would be business suicide to purchase ruthlessly at peak prices. Yet, the State of California paid war time prices for this land and attempted to re-sell it at a price that is far beyond the purse of the average pioneer. This has much to do with the Colony's failure. Another bad feature was the high pressure method advocated by those in charge. Ranchers, old timers in the vicinity, used a different method. Instead of rushing a big acreage of fruit trees into a soil that fell short of the necessary fertility to mother them, and, then starve them to death for six years, until a hoped for crop materialized, your old timer played the game differently. He planted to alfalfa, procured cows, built up the soil gradually and eventually arrived at the fruit stage. It was a slow, tedious method but a reasonably sure one. And he did not pay exorbitant [sic] prices for the land either.

The writer came here with nearly six thousand dollars. He was advised to plant fifteen acres of peach trees. In four years of outside work and putting every cent earned into the upkeep of these trees, he has learned that he should have possessed nearer sixteen thousand dollars than six. And the end is not yet. Everything that he contracted with the State to do for him was done in a slip shod manner. His place was graded in such a manner that irrigation was almost impossible and Dr. Mead, expert tho he might be, would have to apply the Einstein theory with reverse English to get water to run over the land. And this was but one of many setbacks received.

Costly mistakes, errors of judgment, commission and omission, were made by the so-called experts here. Add to this inefficiency, carelessness, and a broken morale thru living in chicken houses upon the advice of officials [who] built for themselves fine, stucco bungalows complete in every detail from breakfast nooks to open fire places. And you have another angle of the situation. Glaring mistakes of engineers and near engineers have complicated things. And for these mistakes and an extremely costly administration the settler is expected to pay. Why, at one stage of the proceedings, pedestrians had to be exceeding alert that they might evade being run down by cars bearing officials and others employed by the state. Any settler at this stage of the game, that was making a showing, was either working for the state, had a good outside job or, a rich father that contributed to the cause. They did not make it off their allotments and they are not making it today.

Engineering blunders have made irrigation costs extremely high. And the cost of the irrigation system adds to the ranchers' overhead. In brief, "Nero fiddling while Rome cracked had nothing on the system used here in the olden days."

As a direct consequence of all this, settlers have pulled out by the score leaving the savings of a lifetime in these drifting sands. Does anyone question the deplorable fact that these losers go back East with a story that gets gloomier at every telling and California shares more than its due of bad advertising as a result? This is one of the objectionable features of the Mead plan. For it has been proven time and again that the original settler, as a rule, loses out. The man that pioneers; paves the way; bears the hardships and risks all his all is not the man that eventually owns the land. It has proven so on every reclamation project; government or otherwise.

Governor Richardson's recent telegraphic message to Secretary Work shows that his excellency realizes fully the white elephant left his administration as a legacy from the Mead faction. And we desire to compliment the Governor for daring to speak the truth. His message plainly showed he was a poor politician but a real he-man.

In a spirit of giving credit where credit is due we cannot honestly hand Ellwood Mead any bouquets on the Delhi venture. Or his much touted plan. Land settlement is as old as Moses;

the original irrigation expert, and outside of the big one in Utah and a few others founded by one nationality, have proven failures.

But publicity goes a long way to make a man famous. One requisite a Mead superintendent must have; besides that human touch, that the celebrated Doctor preaches but, fails to practice here, is to be an able press agent. Articles lauding the project and its founder emanate from this source at regular intervals.

The more we see and hear of reclamation schemes the more we become convinced that Barnum should have raised the ante.

Altho the half of it has not been told we will have to stop for ten newspapers the size of the Record could be filled with the "Story of Delhi."<sup>224</sup>

The editorial is an excellent illustration of the forcefulness with which the settlers presented their arguments and the skill with which they set administration against administration.

With the findings of the investigating committee before them and spurred on by the attitude of the Governor and pressure from the settlers, the Legislature quickly passed some relief measures. A \$350,000 book appropriation was made to remit interest charged against the State Land Settlement Board for previous appropriations.<sup>225</sup> This was the legal method of canceling the interest that the Board could not pay the state. The Legislature appropriated \$250,000 to provide some badly needed cash.<sup>226</sup> After considerable negotiation with the settlers, the Board was able to work out a formula for adjustment which was applicable in equal degree to every allotment.<sup>227</sup> Under it the state agreed to accept 1 per cent interest on all land contracts for the following five years and to reduce the debt of the settlers. The reductions included one of 15 per cent on the land contracts and one of the interest compounded at 3 per cent on 30 per cent of the initial purchase price of land from the date of original contract to July 23, 1925. Also, settlers who had borrowed from the Federal Land Bank were allowed a reduction to an amount equal to the initial costs in connection with the Federal Land Bank loan, together with interest on that amount from the date of the loan, and an amount equal to the difference between the 5½ per cent interest charged by the Federal Land Bank and the 5 per cent charged by the state. The state assumed, moreover, the Federal Land Bank loans and gave the settlers new purchase contracts for the amount due.<sup>228</sup>

The average reduction of indebtedness of settlers on farms of over 13 acres was from \$352.81 to \$305.05 an acre. The average reduction for poultry farms, 3 to 13 acres in size, was from \$369.85 to \$341.03 an acre. The reductions are of the indebtedness of settlers and not necessarily of the allotments owned by them. A number of the settlers exchanged allotments and thus their new indebtedness applied to a new acreage. This was particularly true for the laborers' allotments where so many moves were made to allotments of higher value and thus higher indebtedness that no book reduction in debt per acre occurred. Their debt, after the adjustment, averaged \$547.85 per acre.

Some settlers did not receive much help from the adjustment: 7 of these, including 1 on a laborers' allotment, 1 on a poultry-farm allotment, and 5 on

<sup>224</sup> Anonymous. The truth hurts. [Editorial.] *Delhi Record* 2(10):2. April 16, 1925.

<sup>225</sup> California Statutes, 1925. Chap. 302.

<sup>226</sup> *Ibid.* Chap. 205.

<sup>227</sup> *Ibid.* Chap. 206 and 241.

<sup>228</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of June 30, 1925.] (Typewritten.) See also: [Report on the Delhi State Land Settlement as of July 24, 1925.] (Typewritten.)

farm allotments, were so indebted that even after the adjustment they had no equity. The auditor described their situation as follows:

Seven settlers will have to be dispossessed at the earliest possible moment. . . . If the improvements owned by them could be sold immediately at full appraisal value, the state would suffer no loss. This is, of course, impossible and the necessary termination of the contracts leaves these unfortunate settlers out in the cold. They lose their cash investment and the labor of years. Only special emergency relief could grant compensation in these cases.<sup>222</sup>

Six others had such a small equity that they could stay on their farms only under special contracts.

The total loss sustained at this time by the state is not easy to determine. The state held 3,725 acres of land, or 44 per cent of the settlement area. By legislative enactment, a total of \$350,000 had been written off the books. On September 30, 1925, the auditor announced a deficit of \$72,164, which would probably never be paid or even materially reduced. The relief measures allowed the interest on land contracts held by the state to be 1 per cent. In turn the state paid the Federal Land Bank 5½ per cent on its loans. Thus the state was subsidizing the settlers heavily. The \$250,000 appropriation was largely a relief measure, not an investment. The auditor estimated "a definite loss to the state due to land settlement activity exceeding \$825,000."

The adjustment, no matter how expensive to the state or how inadequate to some individual settlers, immediately eliminated all delinquencies, reduced the settlers' debt materially, and lowered the interest rate on land contracts to 1 per cent. This gave many settlers new hope. Their feelings were expressed by the editor of the local paper as follows:

It is with gratification and joy that we learn, just as we go to press, that Governor Richardson has signed the four Delhi relief measures, thus bringing to a close a long fought and trying battle. The signing of these bills means much to this Colony. The energetic settler, the man who is in earnest and willing to sacrifice, can now succeed. But individual effort is just as essential now as before the bills were signed. The big point is in the knowledge that the State has now kept faith. We can now proceed with our development of our allotments; of our home and our community with the knowledge that we have more than even chance to ultimately succeed. To those who sacrificed so much to bring this relief about; we owe much. Their's [sic] was not an easy task but, rather, in many ways, a thankless one.

From now on let us make the best of the relief extended us. Let us coöperate in every possible way; live as neighbors and friends with the same problems and griefs should live, ever remembering that in helping each other we best help ourselves.

The world will soon forget the publicity we have had. From now and henceforth be a booster. With the proper spirit and right sort of advertising, we're due to surprise even ourselves with the strides we are to make towards success and a bigger, better and broader colony. Victory is ours—Let us not turn it into defeat.<sup>223</sup>

The old community spirit was revived for a time and everyone celebrated in a grand "jamboree," as they called it. Everybody came in some substitute of an early pioneer wagon drawn by horses, mules, cows, or whatever else was available. Some fifty of these wound their way out over the sand dunes, were attacked by "Indians," but managed to reach the river flats where a great picnic was enjoyed by all, settlers and state officers alike.

<sup>222</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of July 24, 1925.] (Typewritten.)

<sup>223</sup> Anonymous. Victory. [Editorial.] *Delhi Record* 2(16):2. May 28, 1925.

## FINAL ADJUSTMENT BETWEEN THE SETTLERS AND THE STATE

The improved feeling which followed the 1925 adjustment at Delhi was short-lived. As has been described, each year brought more production problems and the economic condition continued to be discouraging. On June 30, 1927, the total amount due and delinquent from settlers at Delhi was \$62,541.74, and at Durham was \$110,666.22.<sup>231</sup> Agitation grew stronger each year for another adjustment of debts, this time at both settlements.

Mr. C. C. Young became Governor in 1927. His first step was to reorganize the settlement administration. The Legislature reduced the Board to three in number consisting of the Director of Agriculture, the Director of Public Works, and the State Engineer. A Division of Land Settlement was established in the Department of Agriculture.<sup>232</sup> The Governor appointed Mr. C. W. Cleary as chief of this division. Captain J. Winter Smith was retained as superintendent at Delhi but Mr. O. W. Bauer was appointed to succeed Miss Marshall as superintendent at Durham.

In order to obtain a better picture of the settlements the Governor appointed a citizens' committee to investigate. They reported as follows:

We find that land settlement under the State auspices and direction from its inception was a mistaken theory.... we earnestly recommend that no other or further attempt be made in that direction.<sup>233</sup>

While the attitude of the new administration is not entirely clear, it seems evident that almost from the start the Governor and his advisors determined to withdraw the state from settlement activity.<sup>234</sup> Necessary legislation, however, was not passed until 1929. This legislation included an appropriation of \$185,000 to complete payment on the Stanford contract at Durham,<sup>235</sup> a \$150,000 appropriation to pay readjustment expenses,<sup>236</sup> and the acts authorizing adjustment credits.<sup>237</sup> The 1931 Legislature abolished the State Land Settlement Board and the Division of Land Settlement and turned such credits as remained over to the Division of State Lands in the Department of Finance.<sup>238</sup>

The enactment of legislation, however, was the simplest part of the task. An agreement had to be worked out with every settler, no easy task, for almost every settler had real or imagined claims against the state and was in a position to make his demands effective. The purpose of this section is to describe the factors which led the state to relieve the settlers of most of their debts and thus assume the losses involved.

<sup>231</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Delhi State Land Settlement as of June 30, 1927.] (Typewritten.)

<sup>232</sup> California Statutes, 1927. Chap. 558. (The Director of Finance was substituted for the State Engineer in 1929. See: California Statutes, 1929. Chap. 352.)

<sup>233</sup> California Department of Agriculture, Division of Land Settlement. Final Report. June 30, 1931. *op. cit.* p. 10.

<sup>234</sup> Hecke v. Riley. (1930) 209 Cal. 767.

Anonymous. State planning to withdraw from colonies. *Delhi Record* 5(21):1. June 29, 1928.

Hecke, G. H., Director of Department of Agriculture. State to step out of harness in land settlement soon. *Delhi Record* 7(34):1. September 19, 1930.

<sup>235</sup> California Statutes, 1929. Chap. 11.

<sup>236</sup> *Ibid.* Chap. 626.    <sup>237</sup> *Ibid.* Chap. 352.    <sup>238</sup> California Statutes, 1931. Chap. 153.

### COLLECTION POLICY

Tables 8 and 9 show the development of delinquencies at the two settlements. The accounts receivable can be regarded as transferable in part to the deferred status and in part to the delinquent status. Some of the figures for amounts due the Federal Land Bank are approximations. The decrease in delinquencies at Delhi after December 31, 1924, was due to special extension notes which Mr. Wooster substituted for the delinquencies. These notes, along with the Federal Land Bank loans, delinquencies, and accounts receivable were accu-

TABLE 8  
SUMMARY OF SETTLERS' INDEBTEDNESS AT DURHAM FROM 1918 TO 1928

Date	Indebtedness to state			Indebtedness to Federal Land Bank	
	Total contract indebtedness		Accounts receivable		
	Deferred	Delinquent			
1. June 30, 1918 . . . . .	<i>dollars</i> 337,571.12	<i>dollars</i> 2,262.15	<i>dollars</i> 1,670.70	<i>dollars</i> 91,000.00	
2. June 30, 1919 . . . . .	609,021.60	15,454.24	17,522.04	...	
3. June 30, 1920 . . . . .	641,295.21	17,082.59	12,796.58	...	
4. June 30, 1921 . . . . .	627,107.59	37,124.17	5,070.73	...	
5. June 30, 1922 . . . . .	658,077.74	63,904.50	7,058.25	...	
6. June 30, 1923 . . . . .	628,319.89	84,437.21	4,342.43	...	
7. February 29, 1924 . . . . .	587,879.20	73,498.00	2,098.85	....	
8. August 31, 1925 . . . . .	505,892.30	80,290.57	1,587.37	....	
9. August 1, 1927 . . . . .	470,263.47	102,336.31	1,683.74	....	
10. October 31, 1928 . . . . .	435,534.97	118,611.27	1,773.95	62,068.44	

Sources of data:

Indebtedness to state:

Line 1: California State Land Settlement Board. Report . . . June 30, 1918. *op. cit.* p. 17.

Lines 2, 7, 8, and 10: California Department of Finance, Division of Budgets and Accounts. Report . . . (as of date given). (Typewritten.)

Line 3: California State Land Settlement Board. Report . . . September 30, 1920. *op. cit.* p. 62.

Lines 4 and 6: Files of Giannini Foundation.

Line 5: California Department of Public Works, Division of Land Settlement. Report . . . September 1, 1922. *op. cit.* p. 34.

Line 9: Cleary, Charles W. Division of Land Settlement. California State Dept. Agr. Mo. Bul. 16 (12):755. November, 1927.

Indebtedness to Federal Land Bank:

Files of Division of State Lands. Sacramento, California. (Incomplete.)

mulated and adjusted into one item on July 24, 1925. The important information contained in these tables is that the settlers became more and more involved in debts, due and delinquent.

These delinquencies raise the question as to what policy the various administrations followed regarding collections. An early indication of a policy and a difficulty is revealed in the June 30, 1918, statement of the Durham settlement. Although the first sales of land had been made in that month, past-due items had already appeared on the books. On the initial payments on 3 improvement contracts, \$1,059.15 was due; on the initial payments on 3 improvement contracts, \$1,203.00.<sup>28</sup> At Delhi, also, delinquencies were, from the first, allowed to stand on the books. The first settler's contract was signed on May 26, 1920. The trial balance of June 30, 1920, shows \$3,947.93 as due on settlers' contracts, which in total amounted to \$178,400.29. These delinquencies involved

<sup>28</sup> California State Land Settlement Board. Report . . . June 30, 1918. *op. cit.* p. 20-21.

13 of the 45 settlers.<sup>240</sup> The items were all due as down payments. Although, according to the law, the contracts were not delivered until the required down payment had been made in full, settlers learned early that an item "amount due" on the books did not affect their status and that money for development was still available.

Throughout the years under survey the collection policy was uniformly lax. Statements were issued threatening foreclosure, settlers were billed and called on by officials, policies were discussed, but no strong consistent action was ever taken.

TABLE 9

## SUMMARY OF SETTLERS' INDEBTEDNESS AT DELHI FROM 1920 TO 1928

Date	Indebtedness to state			Indebtedness to Federal Land Bank	
	Total contract indebtedness		Accounts receivable		
	Deferred	Delinquent			
1. June 30, 1920	<i>dollars</i>	<i>dollars</i>	<i>dollars</i>	<i>dollars</i>	
178,400 29	3,947 93	2,009 16	..	..	
2. June 30, 1922	920,024 93	47,458 19	28,644.29	.....	
3. December 31, 1922	1,071,402 13	73,445 27	49,150.11	110,011 01	
4. December 31, 1923	1,147,677 12	128,157 11	58,662 94		
5. December 31, 1924	1,107,173 23	226,001 42	27,002 09	315,100 00	
6. June 30, 1925	1,233,176 13	88,360 57	38,868 76	295,669 31	
7. July 24, 1925	1,438,069 79	..	..	..	
8. June 30, 1926	1,353,031 52	38,628 01	11,138 77	.....	
9. August 1, 1927	1,275,641 21	45,817 52	9,789 25	.....	
10. June 30, 1928	1,232,896 56	80,466 71	15,665 53	.....	

Sources of date:

Indebtedness to state:

Line 1: California State Land Settlement Board. Report . . . September 30, 1920. *op. cit.* p. 64.

Line 2: California Department of Public Works, Division of Land Settlement. Report . . . September 1, 1922, *op. cit.* p. 60.

Lines 3-8, 10: California Department of Finance, Division of Budgets and Accounts. Report . . . (as of date given). (Typewritten.)

Line 9: Cleary, Charles W. Division of Land Settlement. California State Dept. Agr. Mo. Bul. 16 (12):753. November, 1927.

Indebtedness to Federal Land Bank:

Files of State Land Settlement Office Delhi, California. (Incomplete.)

One of the earliest attempts made to encourage payment was the circularization among the settlers at Durham of a letter written by Dr. Mead to Mr. Kreutzer:

Durham is being discussed in every state in the Union and it is the greatest single influence in favor of the movement for the reconstruction of farm life in this country.

Whether it will continue to exercise this influence will not depend on anything the State may do. . . . The State is simply a big brother which gives them [the settlers] a somewhat better chance than they would have working alone, but the influence of the settlement is going to depend entirely on what the settlers, individually and as a community do. And the thing that needs to be done now above all other things is to have every settler make his payment when the six months installment comes due. As you know, I am talking soldier settlement from Florida to Maine. . . . If I can say that every settler at Durham, of the original colony has paid his first installment, it will do more to carry conviction into the minds of those vitally interested, but a little afraid, than days of talk that will omit that fact.<sup>241</sup>

<sup>240</sup> California State Land Settlement Board. Report . . . September 30, 1920. *op. cit.* p. 66.

<sup>241</sup> Mead, Elwood. Letter to G. C. Kreutzer. December 11, 1918. (Files of California Department of Finance, Division of State Lands.)

From the very first some of the settlers were loath to pay even if they had the means. While talking over a delinquency with one farmer at Delhi, Dr. Mead noticed the man's automobile and remarked that its sale would pay off the delinquency and that its upkeep would take care of future payments on the farm. The man had a team to take his family to town, and the post office and grocery store were only half a mile away. The farmer, with no hesitation, replied that if it were a matter of keeping the car or the farm, he would keep the car. The administration accepted his statement and did nothing. During these early years quitclaim deeds were given or cancellations made, but always after compromise or after abandonment of the farm by the settler. The only foreclosure proceedings pushed through in these first years at Durham seems to have been due to pressure by the Federal Land Bank, which held a first mortgage. It is significant that year after year a number of men on laborers' allotments were just one year behind in their payments. This failure to make collections resulted in part from a definite policy, described by Mr. Kreutzer as follows:

The delinquencies are not an absolute indication of their true condition. Practically all have assets far in excess of the amounts owing. The act provided and anticipated that loans would be made to settlers to help them develop their farms. We have held those loans down to a minimum. In fact many of the delinquencies as shown were brought about because the settler used his income to develop the farm rather than to borrow. If we should extend the full lending privilege to these delinquents they would be reduced by at least 50 in number. I feel it is not a good thing to do as debts that are due will be paid sooner than debts that are not due. Such due debts keep them from making costly purchases of equipment or other things which, while needed, they can well get on without during these times.<sup>242</sup>

Mr. Packard in his final report stated:

The policy has been to advise a settler to get his farm onto a paying basis as rapidly as possible even if this necessitated a delinquency to the State, because . . . the contracts of purchase must ultimately be met from income from the land.<sup>243</sup>

These statements in conjunction with the cases studied reveal that the primary objective of the financial policies followed was to get every settler possible onto a producing farm.

In some cases it appears that delinquency may have been allowed to develop because of the neighborly and friendly ties that developed between the settlers and local officials. This was perhaps inevitable when consideration is given to the many phases of farm, home, and community life in which the two groups worked together and which aided in developing close friendships. It is apparent in certain cases that the officers in charge did not collect as well as was possible.<sup>244</sup>

Closely allied with this situation was the desire to avoid unfavorable publicity. This desire is understandable, for nothing could be more disheartening or antagonizing to settlers, established or prospective, than foreclosure or ejection proceedings against neighbors.

The only time that strict collection seems to have been seriously considered

<sup>242</sup> Kreutzer, G. C. Letter to C. M. Wooster. December 12, 1923. (Files of C. M. Wooster.) Also see statement by G. C. Kreutzer in: California Department of Finance, Division of Budgets and Accounts. [Report on Durham State Land Settlement as of February 29, 1924.] (Typewritten.)

<sup>243</sup> Packard, Walter E. [Report . . . February 8, 1924.] *op. cit.*

<sup>244</sup> Supporting information is confidential.

by anyone was by Dr. Mead just at the end of his administration. See p. 463.) Action was prevented by Governor Richardson. One can only conjecture what results might have been obtained had Dr. Mead's suggestion been followed.

Succeeding administrations made no material change in the collection policy. Immediately after assuming office, Mr. Wooster issued the following statement:

The policy of the state land board will be to go through with the contracts at Delhi Colony as originally made. The board is convinced that the colony is a going concern and will eventually prove a success. But the board intends to inject business methods and put the colony on a strict business basis. The board expects all colonists to live up to their contracts as originally made.

Any settler in the colony who shows a disposition to make good will receive all the consideration and help possible from the land settlement board. But those who do not try to make good and are agitating in an attempt to discredit the colony are expected to make their payments promptly, or their ranches will be foreclosed and sold to other people who will make good.<sup>245</sup>

This quotation indicates a more stringent control than Dr. Mead had followed; and most settlers and observers at Durham had an impression that Mr. Wooster brought greater pressure to bear there than had the previous administration. In fact one farm was foreclosed. In the main, however, little distinction can be made between the collection policies of the two administrations.

The administration under Governor Young seems also to have followed substantially the same policy. They may have been more liberal, for they seem to have agreed at first to postponement of payments in a great number of cases. Certainly their assumption of control appears to have been followed by a drop in collections. Their views, however, were outlined by the new chief, Mr. Cleary, as follows:

.... any settler honestly endeavoring to meet his obligations, need not fear loss of any opportunity to continue with the purchase of his allotment, while those where evidence shows that they can pay and do not, will receive such consideration as is due them under the circumstances.<sup>246</sup>

The situation regarding collections at this time is shown by some data for Delhi. On an acreage basis the payments on farms during 1927 averaged about \$6 and during 1928 about \$2. These payments may be compared with the average yearly rental paid from 1925 to 1928 of \$8.30 per acre obtained by the Board on 11 similar farms which they had taken back and rented.<sup>247</sup> It must be remembered that it was at this time the settlers came to full realization that they were going to lose most of their alfalfa and orchards. The improvement in spirits at Delhi which followed the 1925 adjustment was now gone. The settlers at Durham were also losing their important crops. The drop in collections at this time probably was very largely due to production difficulties.

An integral part of the collection policy was the adjustment policy adopted for settlers who wished to leave. The outstanding cases were those on the adobe land at Durham. While very meager information has been obtained about these adjustments, it seems evident that as soon as the administration realized

<sup>245</sup> Files of State Land Settlement Office, Delhi, California.

<sup>246</sup> Anonymous. New policy of Delhi announced. *Delhi Record* 4(41):1. November 18, 1927.

<sup>247</sup> Files of California Department of Finance, Division of State Lands.

that the land would not produce as had been anticipated and that the settlers could not succeed, arrangements were made by which the settlers would suffer little loss and yet could continue farming on their better land. Some settlers at Delhi who were found to be undesirable were given an opportunity to make similar adjustments; some, in fact, had their equity returned. The early establishment of these policies had great influence in later years. The settlers did not forget that others had received favorable adjustments when difficulties were met.

The writer believes that a number of the settlers, particularly at Durham, could have paid more than they did, certainly during the early years. Other settlers were doing so with apparently the same opportunity. While this cannot be proved, one may quote the state auditor who as late as 1927 claimed that collections could have been better. He said:

Of the \$110,666.22 due and delinquent on June 30, 1927 only 24 per cent have fallen due on last installment period. The remainder represents an accumulation of 10 years. Unquestionably the Board has been lax in enforcing collections. It is interesting to note that there are no delinquencies in Federal Farm Bank collections. Undoubtedly the exclusion of the colony from participation in legislative relief afforded at Delhi, is reflected in a disinclination on the part of certain settlers to meet their obligations to the State. Somehow the impression has gained ground that conditions are favorable to obtain some relief from the State and with that object in view it is not surprising that the delinquencies are mounting. It makes a good talking point. Properly applied pressure with an occasional foreclosure would have a salutary effect in reestablishing the morale and incidentally securing the working capital which is so badly needed. ....

There are 136 land contracts in force. Average holdings are 32½ acres, average delinquency is \$814.00 per settler constituting a delinquency period of a little over 2 years; average equity in land is \$800.00 per man so it is evident that the State must look to the improvements to be safe from loss in case of reversion. Twelve settlers have no equity at all, the amounts owing exceeding their payments by a sum approximating \$11,000.<sup>28</sup>

Whether or not collections might have been better, the fact remains that from the first collections were not made and adjustments were easy to obtain. Regardless of what administration leaders said, their policies encouraged settlers to ask for more and more favorable terms. This was an important fact in the final distribution of losses.

#### THE "PROMISES" MADE IN SELLING THE LAND

The elimination of misleading information in selling land was a fundamental concept in the original settlement plan and the administration stressed the disinterested and unselfish character of its representations. That the interest of the settlers was given consideration is evident by a reply to an inquiry from Kentucky. The applicant was advised not to come because he had been receiving \$3,000 annually and would find a change to Delhi disappointing.<sup>29</sup> Usually, however, favorable aspects were stressed. A letter to a prospective applicant makes, for instance, the following statement.

The land in both settlements was selected by the experts of the University and bought at a price fixed by the Dean of the College of Agriculture and is being sold on terms that give the state back the money invested without a profit. . . . You would pay for established

<sup>28</sup> California Department of Finance, Division of Budgets and Accounts. [Report on the Durham State Land Settlement as of June 30, 1927.] (Typewritten.)

<sup>29</sup> Mead, Elwood. Letter to E. E. Bratcher, Science Hill, Kentucky. January 7, 1924. (Files of Giannini Foundation.)

orchards in . . . [the Santa Clara Valley, Modesto, and Chico] about five times as much as you would for one of the state farms.<sup>250</sup>

In another letter the following statement is made:

These land values are certain to rapidly increase. The development of the settlement, the improvement of the townsite, have all created an entirely different situation from that that prevailed when the price of this land was fixed at \$350 an acre. If we were to revalue it would be put at double that price.<sup>251</sup>

Prospective applicants also were told to expect a high yield of alfalfa. Though the first stands of alfalfa at Delhi had been poor, applications of sulfur and of ground limestone and sulfur had been successful, and the Board, feeling that good crops would continue, made such statements as the following:

We bought several carloads of lime and lime sulphur for settlers at Delhi. Last year the lime sulphur gave fine results and this year we are encouraging settlers to use it under an arrangement that if there are no results from lime sulphur, the state will pay for the fertilizer. The results last year were so striking that we do not feel that this offer involves any risk.<sup>252</sup>

It was repeatedly asserted that alfalfa yielded 6, 7, and 10 tons an acre. Official advertising of the Board carried the following statement:

The soil is particularly suited to alfalfa. In 1922, the second year of settlement, two and one-half to three tons in single cuttings have been secured on the settlement. . . . It is estimated that the alfalfa fields will yield an average of eight tons to the acre in 1922. Five cuttings are always secured and sometimes six during the year.<sup>253</sup>

The following letter is typical:

Last year crops of alfalfa yielding ten tons to the acre were grown not on one farm but on several.<sup>254</sup>

The Santa Fe, in its advertising, described the situation as follows:

A twenty-acre farm, planted say five acres to alfalfa (which will take care of five cows), about five acres for some grain, nine acres equally divided between trees and vines, reserving one acre for house, barn and garden, makes a well balanced place. The trees and vines can be inter-planted with melons, cantaloupes, sweet potatoes, or tomatoes—all of which will do well and make profitable returns. It is represented by the Chairman of the Settlement Board that the returns from three cows will meet the annual land and interest payments.<sup>255</sup>

This last statement about the returns from three cows was often reiterated.<sup>256</sup> The profitability of peaches was also assured by statements such as the following:

The production of fruit, especially peaches and raisin grapes, will ultimately be the most

<sup>250</sup> Mead, Elwood. Letter to G. P. Butters, Westmount, Canada. March 5, 1923. (Files of Giannini Foundation.)

<sup>251</sup> Mead, Elwood. Letter to A. H. Thompson, St. Lawrence, South Dakota. February 27, 1922. (Files of State Land Settlement Office, Delhi, California.)

<sup>252</sup> Mead, Elwood. Letter to Fred Kiesel, Sacramento, California. March 6, 1922. (Files of Giannini Foundation.)

<sup>253</sup> California Department of Public Works, Division of Land Settlement. Information for intending settlers regarding the Ballico unit of the Delhi Land Settlement. September, 1922. (Broadside; in files of Giannini Foundation.)

<sup>254</sup> Mead, Elwood. Letter to G. H. Hensley, Phelps, Wisconsin. March 27, 1923. (Files of Giannini Foundation.)

<sup>255</sup> Seagraves, C. I. Circular letter. The Atchison, Topeka, and Santa Fe Railway Company. (Files of Giannini Foundation.)

<sup>256</sup> California State Land Settlement Board. Report . . . September 30, 1920. *op. cit.* p. 45.

important industry in the settlement. The soil is well adapted to the production of good peaches.<sup>227</sup>

One objective was to give the settlers guidance that would insure success regardless of their previous experience. The following statements by Dr. Mead are illustrative:

One of the objects in the creation of the State settlements in California was to place an inexperienced man on an equality or near an equality with a man who knew just what to do. This is done through there being in each settlement a highly qualified practical adviser who helps the settler to determine what to do and when to do it. We have taken in both settlements people with no experience and they are nearly all successful and go ahead with hope and confidence.<sup>228</sup>

Answering your question about starting without experience, there is always some risk in doing this and it is impossible to say yes or no to your inquiry of whether one starting, as you express it, "entirely green," can succeed, but this can be said. The chances of people succeeding in these state settlements where they have the help of an expert farmer as an adviser, where the people are organized to cooperate, where they meet together to discuss their farming problems, are far greater than they are where a man is turned loose to find out for himself and some of our most successful settlers were city people with no farming experience whatever.<sup>229</sup>

It is always better to see a place before buying, but, where this is not possible, you need have no misgiving as to any misrepresentation on the part of the state authorities in regard to these lands. You will understand that the state is not in this business to make money but to create new communities of contented, successful people and we have endeavored to have the value of different farms so adjusted as to make them all equally attractive. Selection is, therefore, a matter of personal choice. If it is left to the Delhi authorities they would, of course, choose the one that makes the strongest appeal to them, and their judgment is probably better than yours.<sup>230</sup>

Another element in the land-sales program was the repeated assurance that liberal credit was available. All the settler had to do was to meet the minimum capital requirement and make the down payment. These assurances continued even after officials realized that money might run short. Mr. Kreutzer on his trip east in the spring of 1923 advertised as follows:

Millions of dollars have been spent to make them (the settlements) ready for colonization. And money will continue to be spent for no other reason than to help the new settler work out his problem.<sup>231</sup>

That this phase of the program was stressed is shown in the following statement:

Practically every settler in Delhi was sold carrying an obligation on the part of the state to loan him necessary money for development. This appears to be a definite obligation. The mere acceptance of a settler, who on the face of it had insufficient capital to succeed without loans would bind us to this policy. In addition the office files disclosing relations with indi-

<sup>227</sup> California Department of Public Works, Division of Land Settlement. Report... September 1, 1922. *op. cit.* p. 43.

<sup>228</sup> Mead, Elwood. Letter to R. C. Baker, Portland, Oregon. February 13, 1923. (Files of Giannini Foundation.)

<sup>229</sup> Mead, Elwood. Letter to Chester J. Lothian, Effingham Falls, New Hampshire. March 2, 1923. (Files of Giannini Foundation.)

<sup>230</sup> Mead, Elwood. Letter to H. H. Koch, Dickinson, South Dakota. March 5, 1923. (Files of Giannini Foundation.)

<sup>231</sup> California Department of Public Works, Division of Land Settlement. [Announcements of G. C. Kreutzer's trip to the Midwest. January, 1923.] (Advertisements; in files of C. M. Wooster.)

viduals would bind the State to this policy almost without exception. This has been one of the strongest and the outstanding sales argument.<sup>203</sup>

Although no exact conclusions can be drawn as to how typical the foregoing statements were, the replies to hundreds of inquiries provide evidence that similar statements were common. The settlers constantly referred to the "promises" of the state officials and they became one of the most important factors in the final agreement.

#### **RESPONSIBILITY OF THE STATE FOR ITS "PROMISES"**

As the settlers came to understand the situation at the settlements, they began to claim that these "promises" constituted a foundation for a charge of fraud and misrepresentation. At Delhi no suits were ever instituted against the state but at Durham a number were threatened and a few were prosecuted. One of these is of interest here since it had to do with these charges.

In 1918 the Board sold Mr. H. H. Dingman a 40-acre farm for \$8,366.40. He placed improvements on it valued at \$5,500. He was unable to raise good crops and almost from the start was delinquent in his payments. In 1921 he left the place and leased it until 1924 when Mr. Walker offered him \$5,500 for his equity. This, with the debt to the state, made a price of \$12,772.19. Superintendent Kreutzer and the Board's Secretary represented Mr. Dingman in making the sale. Mr. Walker moved onto the place in the spring of 1924. The next winter the water table rose; the alfalfa and prune trees that year either died or produced very poorly.<sup>204</sup> Thereafter only shallow-rooted crops would grow on the farm. In 1927 Mr. Walker sued the state for damages. The Appellate Court described the suit as follows:

Two causes for action were alleged. The first count charged Kreutzer as Superintendent of the State Land Settlement Board, . . . . and [the Board's Secretary] with fraudulently representing to the plaintiffs that the land was perfectly drained and was exceptionally well adapted to the growing of prune trees and alfalfa [and] would support at least one cow per acre. . . . The second count alleges loss and damages to the prune trees and alfalfa . . . . on account of negligence on the part of the board in constructing and maintaining an irrigation system with open ditches and which permitted the percolation of water through the soil of plaintiff's land, destroying the prune trees and alfalfa and ruining the fertility of the soil.<sup>204</sup>

<sup>203</sup> Cook, Max. Existing conditions Delhi administrative affairs, April 1, 1924. (Type-written; in files of State Land Settlement Office, Delhi, California.)

<sup>204</sup> During 1923, the year before Mr. Walker purchased his farm, the rainfall was 15.08 inches, far less than the average since 1870 of 23.74 inches. The rainfall for each year after the settlement started was as follows:

Year	Inches	Year	Inches
1918	21.43	1923	15.08
1919	21.74	1924	22.36
1920	31.74	1925	22.51
1921	23.57	1926	33.16
1922	27.41		

The rainfall during the period July 1, 1923, to June 30, 1924, was 14.81 inches and during the following 12-month period was 23.13 inches. In 1925 after a very dry spring, 4.09 inches fell in April, much later than usual. It is apparent that Mr. Walker purchased his farm at the end of an exceptionally dry period. These data are from the Chico station located about 3 miles from Mr. Walker's farm. (Data for 1870 through 1903 from: Henry, A. J. Climatology of the United States. U. S. Dept. Agr. Weather Bureau Bul. Q:981. 1906. Data for 1904 through 1926 from: U. S. Dept. Agr. Weather Bureau. Report of the Chief of the Weather Bureau. Annual issues.)

<sup>204</sup> Walker v. State Department of Public Works. (1930) 108 Cal. App. 508.

In the trial a number of witnesses were heard who supported or contradicted the charges. It is noteworthy that nothing was presented concerning the early recommendations of the engineers that a more extensive drainage system would be needed. It is also noteworthy that witnesses introduced by the state agreed that the current value of the farm was only \$5,000. The attorneys for the state always agreed that the plaintiff had suffered severe losses. For instance, in the hearing before the appellate court they made the following statement:

It is a fact in this case that after the sale the land proved for the time being to be unsuitable to alfalfa, prune trees or beets and that for a period of time, until such changes could be made in the irrigation and drainage systems as would lower the water table, the land would not have the value and productive capacity that Mr. Kreutzer . . . regarded it as having.<sup>285</sup>

It is not to be thought that by these admissions the attorneys for the state were admitting all the claims of the plaintiffs. Rather they centered their defense around the charge of fraud and misrepresentation which they maintained was untrue. They regarded the fact that Mr. Walker had found the land to be unproductive as no proof that Mr. Kreutzer knew it and purposely misrepresented the character of the land.

The court of first instance with the aid of a jury gave judgment in favor of Mr. Walker and awarded him \$7,500. On appeal this judgment was reversed and the case returned to the lower court. The appellate court's ruling was based only on the first cause but as the jury in the trial court had not distinguished between the two causes, the appellate court, having found one cause was insufficient, had to reverse the entire judgment. The court ruled as follows:

Since it is apparent the board had no legal authority to sell this land which belonged to Dingman, the representations of neither Kreutzer nor . . . [the Board's Secretary] could bind it, assuming that the statements constituted fraud and deceit.<sup>286</sup>

The court in its decision supported the defense of the attorneys for the state and emphasized that Mr. Dingman held legal title to the land, that this ownership was known by Mr. Walker, and that,

. . . the plaintiffs were bound to take knowledge of the statutory limitations of authority on the part of the Board to resell only such land as it actually owned and controlled.<sup>287</sup>

While this technical point was the major reason for reversing the judgment, the court also ruled:

We are of the opinion the record will not sustain the charge of fraud and deceit which is alleged in the first cause of action for the reason that the evidence refutes the possession of knowledge . . . that . . . [the statements] were untrue.<sup>288</sup>

This was the only serious attempt by a settler to establish in court a charge of fraud and misrepresentation. Most settlers, however, claimed that the state was obligated to them. This had been expressed by the attorney for Mr. Walker as follows:

. . . it appears to the writer that the State Land Settlement Board had established a confidential relationship between its officers and settlers by representing in published litera-

<sup>285</sup> *Walker v. State Department of Public Works*. (1930) 108 Cal. App. 508. Appellate Record, Third District, Civil 3944. Appellant's opening brief, p. 17-18.

<sup>286</sup> *Walker v. State Department of Public Works*. (1930) 108 Cal. App. 508.

<sup>287</sup> *Ibid.* p. 515. <sup>288</sup> *Ibid.* p. 516.

ture that the State would advise colonists in all matters relating to the purchase and farming of their allotments, and by actually undertaking to do so, it lulled the settlers into a sense of security, for they believed that with the guiding hand of the State represented by its expert officials, they could not err, and they placed express and implicit confidence in the advice given. While of course there is no confidential relationship generally between officials of the State and the public dealing therewith, the writer believes that the State Land Settlement Board itself sought to and did create that relationship, by virtue of its numerous pamphlets, circulars, and literature, wherein the picture of Land Colony life was glowingly made, for the express purpose of inducing people to purchase, and entrust the selection of their allotments and the handling of their individual farms to the guiding hand of the State.<sup>209</sup>

The same attitude is expressed by another settler at Durham in his application for a more liberal adjustment than he was first offered.

I am sixty-five years of age; my wife is sixty-three. We bought this property eight years ago, in 1922. It was represented to me to be, and I believed it to be alfalfa land. ....

The second year I was there, I planted about one-half the land to alfalfa. I expended the little money that I had after making my initial payment, in purchasing dairy equipment, because I was advised to do so, and that that was what it was fitted for. This advice was given me, of course, by the State's agents. The first year I raised enough alfalfa to feed seven head of cows. The second year I had enough for nine and sold three loads of hay, but by the third year, the alfalfa was mostly gone. It was gone because it had lived as long as alfalfa can be made to live on that soil. It dies because of the high water table. I was forced to sell my cows at a loss.

At this time I requested the superintendent to permit me to sell my allotment and to buy a cheaper allotment with less improvements in its place. If I had been permitted to do this, I could have kept my payments up, but the State refused to permit me to do so. ....

.... I was assured that with the means available, I, or anybody else, could make a go of it. I put all that I had into improvements and payments and most of the money that came from crops—keeping out only enough to secure absolute necessities for myself and wife. The only crops that I can raise on my place are short-rooted crops, such as beans and corn, and grain.

I believe my allotment was priced too high in the first place. ....

We were assured that we would have a drainage system that would afford proper drainage for the land, but no system has ever been supplied to take care of the drainage water and the natural drains and those that originally afforded drainage, have been filled up and the land suffers in consequence.

My place had a ditch along the East side which was about eight feet from my boundary line. This strip, extending the entire length of my place, was useless unless I moved the ditch over to my line so as to be able to cultivate more of my land. This I did at considerable expense. I was charged for the cost of constructing this ditch as an improvement, and as a matter of fact, it was no improvement at all, for it was in the wrong place, and I had to, and did, change its location, as above stated. ....

My money is all gone and I have suffered a very substantial loss by attempting, in good faith, to prove the land to be adapted to the crops that I was assured it was adapted to, but was not, in truth and in fact, adapted to produce such crops.

I feel that the additional allowance requested is no more than is reasonable under all the circumstances, and I know that if the State will settle with me upon the basis I desire, it will receive the full worth of the land I am purchasing.<sup>210</sup>

A similar attitude was expressed by a Delhi settler as follows:

Most of us know from direct experience this soil will not yield much beyond a living for the farmer even in good times and that it is impossible to pay our present indebtedness from the products of the land. I wonder if even you are aware of the large number of well-developed farm homes that have been abandoned or leased for little or nothing because the owners themselves were unable to make even a living from them. When we consider that during the past nine years the land has been at least as productive as it will be during the

<sup>209</sup> Walker v. State Department of Public Works. (1930) 108 Cal. App. 508. Appellate Records. Third District. Civil 3944. Points and authorities of respondent on appeal. p. 34.

<sup>210</sup> Letter. (Files of California Department of Finance, Division of State Lands.)

next eight years and the prices for products higher we must conclude that the contracts which the State holds are of little value. The Book Value of the State's equity is so pleasant to look at and the actual depreciation of those values so unpleasant to consider that the State is finding it difficult to put the plans for reconstruction on a basis where the land can pay out. It is difficult to estimate how much the settlers have put into this colony in cash. Probably not less than \$900,000 in money and \$1,500,000 in labor or a total of \$2,400,000. As matters stand today this is practically a total loss to the settler for with the exception of personal property, live stock, etc., there is no salvage value.

We as a committee stand firmly on this, that we will not agree to any plan of reconstruction that is not based on the capacity of the farms to pay.

.... this is not an action against the State, but simply a sensible business move on our part.

We believe that any ideas of revenge or coercion should be left out of any plan of reconstruction and we have based all consideration on a fair and equitable basis to ourselves and to the State and ask you to do the same.<sup>27</sup>

The attorneys for the Division of Land Settlement described the problem as follows:

There are very many settlers who are in default on their contracts. Many of them owe to the state much more than their land is worth. If the state should foreclose the contracts it would be put to the expense of a law suit in practically every case, because the settlers are in a mood to fight every move of that sort that the state might make, and they would have the support of the public and of the trial courts and juries. The state would be put to heavy expense in the trial of the cases and would at best recover the possession of land that it could not resell for as much as it can get from the present contract purchasers upon a readjustment of their contracts based on the actual situation.<sup>28</sup>

The statement just quoted was from a hearing before the California Supreme Court on the constitutionality of the final adjustment. It was a petition for a writ of mandate to force the State Controller to honor warrants drawn to the credit of a settler. The attorney for the Controller stated the question as follows:

.... "the adjustment" means that in the judgment of the Director of Agriculture, the price .... [settler] paid for the land was too much, and he is to be presented with the sum of Twenty-four hundred and seventy-eight dollars (\$2478.00) of public money, representing, in effect, the difference between what he agreed to pay and did pay for the land, and what it is now figured he ought to have paid, and the question is whether or not the act of the Legislature .... under which this adjustment was accomplished, is lawful and constitutional.<sup>29</sup>

The attorneys for the Division of Land Settlement replied as follows:

Such is counsel's impression of the situation, and it represents the background for his arguments. But we have been in close touch with land colony administration. We know just what sort of mess the colonies have been and now are in and how imperative it has been and is that the state get out of the business as expeditiously as possible. The law as it was drawn was applied to those facts. .... [settler] did, in the light of subsequent experience, pay too much for his land.<sup>30</sup>

<sup>27</sup> Batterman, W. S. [Speech at Delhi, November 9, 1928.] In: Settlers' executive meeting was held Friday night; proposition discussed. *Delhi Record* 5(41):4. November 16, 1928.

<sup>28</sup> Hecke v. Riley. (1930) 209 Cal. 767. S.F. 13,889. Reply brief on behalf of petitioner. p. 40. (Typewritten.)

<sup>29</sup> Hecke v. Riley. (1930) 209 Cal. 767. S.F. 13,889. Respondent's points and authorities in support of demurrer to petition for writ of mandate. p. 2. (Typewritten.)

<sup>30</sup> Hecke v. Riley. (1930) 209 Cal. 767. S.F. 13,889. Reply brief on behalf of petitioner. p. 39. (Typewritten.)

The court upheld the constitutionality of the act in a decision which read in part as follows:

When the Legislature has stated that protection and conservation of the investments already made and the welfare of the settlements will be subserved by the withdrawal of the State from further responsibility in respect thereto, the Legislature has stated a public purpose and whatever moneys are necessarily spent pursuant to the authority given, though incidentally they may also benefit personally the settlers to whom such payments are made, do not constitute a gift of public moneys,....

.... we are also of the opinion that a proper construction of the act leads to the conclusion that no payment of moneys or allowance of credit is contemplated unless the same be in consideration of the extinguishment of obligations existing or to arise against the State Land Settlement Board or its successors by reason of their past conduct in the administration of the affairs of the settlements.<sup>275</sup>

These views reveal two basic elements. The first was that the returns from the land were so poor that losses were inevitable. The second element was that the state should bear a large part of the losses involved. The legal obligation on the part of the settlement administration to return to the state all sums used in land settlement<sup>276</sup> and the legal power of the state to foreclose on the settlers and force them to take the first loss<sup>277</sup> were never given serious consideration. The rejection of these written contracts as defining the rights and obligations of the parties concerned and the insistence on intangible and undefined claims arising out of the state's policy of aid and direction led to the confusion and conflicts which are being described.

#### THE IRRIGATION SYSTEMS

Another important factor in the final distribution of losses was that the state had installed and was operating the irrigation systems. The problem was particularly important at Durham. The settlers in later years refused to co-operate in the management of the system there; in fact individual settlers threatened a charge of trespass against state men who were on their farms attending to the irrigation. Some started suits for damages. The second cause for the action started by Mr. Walker was for improper operation of the irrigation system. A similar charge was made by a Mr. Meyer, and at the time of final adjustment he held a judgment for \$9,500 against the state.<sup>278</sup> Under the circumstances the operation of the systems constituted an obligation on the part of the state more important than the obligation of the settlers to pay their debts. The situation was described as follows:

The state has an irrigation system at Durham and another at Delhi. The operation of the systems has been a constant source of annoyance and expense. It is true that the state charges tolls, but they are not a lien upon the land, and if they are not paid, they cannot, in many cases, be collected. The state may refuse to deliver water; if it does the security it has for the payment of the purchase price of the land is impaired. It cannot abandon the irrigation systems without largely destroying the value of the securities and of the lands that it owns in the colonies. It cannot transfer them without finding some organization to transfer

<sup>275</sup> Hecke v. Riley. (1930) 209 Cal. 767. (See especially p. 773-74.)

<sup>276</sup> "A revolving fund to be known as the 'land settlement fund,' which is calculated to be returned to the State with interest at the rate of four per cent per annum within a period of fifty years from the date of the passage of this act." (California Statutes, 1917. Chap. 755, Sec. 25.)

<sup>277</sup> See contracts. (Files of Giannini Foundation.)

<sup>278</sup> Meyer v. State Land Settlement Board. (1930) 104 Cal. App. 577.

them to. In Durham it proposes to turn over the system to a mutual water company, which has been formed for that purpose. But the water company must control the water rights which are owned by the settlers or are held by them under contract. The state cannot transfer them to the water company; it must induce the settlers to do so. It is not essential that all of the settlers coöperate but a sufficient number must do so if the water company is to be able to function with such efficiency as to protect the interest of the state itself. In Delhi the plan is to transfer the system to an improvement district within an irrigation district, and it was found necessary to amend the improvement district law to cover the situation. The improvement district cannot be formed without coöperation from the settlers in the signing of petitions. That coöperation cannot be obtained without the making of allowances and revising the contracts of the settlers.<sup>29</sup>

#### GROUP ACTION

One factor in the strength of the settlers' demands against the state was the group nature of the settlements. Originally adopted in order to facilitate control by the state, group settlement eventually made possible political pressure by the settlers. They could meet together, encourage one another, and take common action. While at Durham individual action seems to have been more important—all suits instituted against the state were by settlers at Durham—group action played some part. During Mr. Wooster's administration and in response to threatened foreclosure, the Durham Settlers' Association was formed. While it never represented many of the settlers, considerable unity was achieved in the settlers' refusal to pay their debts. The word was passed around that no payments were to be made; anyone who paid was regarded by many as disloyal to his neighbors.

At Delhi, however, group action was most important. Illustrative of this action was the community's support of a local weekly, the *Delhi Record*. It was started by the settlement officers as a mimeographed information circular but was taken over as a private enterprise and developed into a country weekly. Throughout the period under survey it served as an important center of information and expression.

The way in which the settlers obtained the 1925 adjustment has already been described (p. 459-67). Their early organization was revived when trouble again developed,<sup>290</sup> and by 1928 they had strong and energetic leadership. The state officers recognized the importance of the settlers' organization and tried to deal with the settlers through it. Thus through this organization the original plan of adjustment, "plan W," was arrived at.<sup>291</sup>

"Plan W."—The amount owed the state by the Delhi settlers on December 31, 1927, was more than \$1,300,000. Mr. Cleary at first suggested that this be reduced to \$550,000, but the Settlers' Executive Committee was reported to have offered only \$250,000. A compromise was made in April, 1929, at \$375,000. This was the amount that the Legislature had in mind when it acted that spring and it was approved at a mass meeting by about 85 per cent of the settlers.<sup>292</sup>

<sup>290</sup> Heeke v. Riley. (1930) 209 Cal. 767. S.F. 13,889. Reply brief on behalf of petitioner. p. 42-43. (Typewritten.) (The improvement district law referred to was California Statutes, 1929, Chap. 189.)

<sup>291</sup> Anonymous. Settlers elect new committee. *Delhi Record* 4(23):1. July 15, 1927.

<sup>292</sup> California Department of Agriculture, Division of Land Settlement. Final Report. June 30, 1931. *op. cit.* p. 12. (This is a valuable publication, for it contains a résumé of the history of the settlements and the views of those who brought about the final settlement.)

<sup>293</sup> Anonymous. Settlers accept state proposal. *Delhi Record* 6(9):1. April 5, 1929.

7 December the details of allocating this reduction among the settlers had been worked out and was presented as follows:

The purpose of this meeting is to explain to the Settlers the plan by which the individual settlers will pay off the obligation of \$375,000 to the State, as was agreed upon April 3, 1929, at Sacramento.

**The Plan—**

1. Settler will be charged with all loans and interest.
2. Settler will be charged with 35% of the 1925 contract price for land plus one per cent interest from date of said contract.
3. Settler will be charged with 50% of the Original cost of Pipe line plus 5% interest from date of installation.
4. Settler will be credited with approximately 11% of the replacement of all improvements except pipe lines.<sup>283</sup>

The settler was to give the state a deed of trust for his remaining indebtedness or if possible pay it outright. If his debt was less than the reduction in value, then the difference would be paid to him in cash. This last cash transaction was necessary to assure a fair deal to any settler who had made a heavier investment than the others and thus had a larger equity. Where the figures showed no settler's equity in the property, the state was willing to take it over, paying \$100 for a quitclaim deed, if the settler so desired. If the settler's equity was so low that he would be unlikely to pay out, the state was willing to purchase the property at the equity shown. If the state officials thought the property was not of the type subject to such purchase, the question was left to an arbitration committee.

To appreciate the settlers' reaction one must know the effect of "plan W" on individuals. Of the 232 settlers at Delhi, 24 would have had nothing more to pay, would have received deeds to their allotments, and would have had additional credit besides; 9 would have had less than \$100 to pay. On the other hand, 13 would have still owed so much that they would have had no equity at all as determined by the new valuation; 30 would have had less than 20 per cent equity; and 117 would have owed more than \$1,000 each even after the adjustment. The great difference in equities is explained partly by the fact that some settlers had borrowed heavily and had made only small payments, whereas others had borrowed less and had kept on paying. The final balance of each was calculated by the equal application of general and proportionate reductions.

The plan represented much work and study and was adopted only after about twenty other plans had been discarded. The leaders hoped that it would be accepted by enough settlers so that the final agreement would go forward without delay. The executive committee had used every resource to reduce the indebtedness to \$375,000, and the land-settlement board had given every indication that a greater reduction would not be allowed.

*Delhi as a "Pressure Group."*—Just when the whole problem appeared solved, a group of settlers began to agitate for more favorable terms.<sup>284</sup> Al-

<sup>283</sup> Delhi Settlers' Committee. Press notice. December 5, 1929. (In files of Giannini Foundation.)

*Also see:* [Delhi Settlers' Committee.] Report of Settlers' Committee, Settlers' meeting. December 5, 1929. (Printed; in files of Giannini Foundation.)

<sup>284</sup> Anonymous. Legion to seek better terms for colonists. *Delhi Record* 6(44):1. December 18, 1929.

Anonymous. Legion rejects adjustment plan. *Delhi Record* 6(48):1. January 3, 1930.

though these men at first constituted only about 40 out of the 232 contract holders, they would owe about a third of the indebtedness remaining after the acceptance of "plan W." By energetic organization and publicity they obtained the support of various state groups and newspapers. Of equal importance, they threw everything into confusion.

In December, 1929, the only group wholeheartedly supporting "plan W" was the Settlers' Executive Committee. The state officials, feeling that the terms were perhaps more liberal than they were justified in allowing, did not immediately agree to accept the plan.<sup>284</sup> Only after considerable urging by the Settlers' Executive Committee did the state officials make it absolutely clear that they would accept "plan W." By this time, however, the minority were strenuously campaigning for more liberal terms. While some objected to the rigid application of the plan to all alike because the settlers differed in their needs, others became more vitriolic than ever in their denunciation of the state. Some declared that the land was worthless and should be given to the settlers. Some said the state should apologize and ask each individual how much it owed him. Another man remarked, "If it is necessary for wives to work like men, the sooner the land is turned back to the jack rabbits and coyotes, the better."<sup>285</sup>

There were innumerable complications. The lawyers consulted found that the 1929 law did not give the State Land Settlement Board power to foreclose on any settler.<sup>286</sup> Rather, the Board was specifically instructed to keep the settlers' welfare in mind and to settle all disputes with them. The administration was required by law to effect an agreement; each settler was free to agree or not. A small minority could prevent the transfer of the irrigation system to the Turlock District. By January there was a question of legality of all proceedings because, according to law, the final agreement should have been concluded by then.<sup>287</sup> The settlers were well on the way to make the issue a political one.<sup>288</sup> To press their case, the opponents of "plan W" began raising money at a dollar an acre to sue the state.

In the meantime Mr. Cleary and the Board had tried to get "plan W" accepted and 65 per cent of the settlers had signed.<sup>289</sup> Mr. Cleary's argument was as follows:

This "write-off" is in consideration of the various mistakes made by the State in connection with the colony including the mistake of starting the project and in consideration of the State's desire to retire from the project as colonization agent. ....

<sup>284</sup> Delhi Settlers' Committee. Press notice. December 5, 1929. (In files of Giannini Foundation.)

<sup>285</sup> Anonymous. Irrigation problems important in settlers' adjustment plans, opinion of Wednesday's meet. Delhi Record 6(49):1. January 10, 1930.

<sup>286</sup> Anonymous. No chance for foreclosure is seen by Mark R. Averill. Delhi Record 6(52):1. January 31, 1930.

<sup>287</sup> "It shall be the duty of the director of agriculture to prepare and present to the state land settlement board for its approval on or before January 1, 1930, a plan or plans for the readjustment of land settlement affairs on a basis which will provide for the withdrawal of the state, not later than four months from and after the final adjournment of the forty-ninth session of the Legislature of the State of California, from the conduct of land settlement or colonization projects." (California Statutes, 1929. Chap. 352, Sec. 5.)

<sup>288</sup> Anonymous. Settlement affair may result in statewide future political campaign weapon, is belief. Delhi Record 6(52):1. January 31, 1930.

<sup>289</sup> Anonymous. Opposers of plan "W" to meet with State Land Settlement Board in Governor's chamber at Sacramento this morning at ten o'clock. Delhi Record 7(2):1. February 14, 1930.

Opposition to "plan W" has to a considerable extent been developed through the circulation of rumors and misinformation. Hysteria and emotion have been aroused where sound sense is needed. A plain statement by the State of a manifestly proper policy regarding administrative procedure under "plan W" has been misconstrued as a threat to compel you to accept the plan.

The State believes that "plan W" offers an ample and generous adjustment, as fairly distributed as conditions will permit; which opinion is concurred in by your committee. In the event that a sufficient number of you accept "Plan W" to establish it as the basis of procedure, this justifies a policy of administration under it respecting those who do not then accept, that provides for due additional notice and a fair opportunity to accept, after which, failure to accept will be construed as an election by the settler to stand on his existing contract and that contract will be enforced to the limit that the law and legal procedure will permit. ....

Should a sufficient number of you be influenced by selfish or misguided leadership or advisers to cause a failure to take advantage of the opportunity to obtain this adjustment, the responsibility for any future distress which you may suffer as a result of such failure will rest upon that leadership and those advisers and not upon the State of California.

This letter is not written in any attempt to coerce or force you to do something against your will but is simply a statement of facts which I believe is due you at this time.<sup>21</sup>

Mr. Cleary sent this letter on January 9, 1930, and during the following weeks made every effort to obtain a more general acceptance. February 14 was set as the dead line.<sup>22</sup> But with the support of important political groups, the opponents of "plan W" had been able to win the Governor's attention.<sup>23</sup> He granted a 60-day delay, called a meeting of the Board and of leaders among the settlers, and asked Mr. E. G. Adams, the local assemblyman, to try to settle the matter. At first, this precipitated a sharp quarrel between the Settlers' Executive Committee and Mr. Adams.<sup>24</sup> The committee wanted no delay because they were always afraid that the state would settle with the disabled veterans and then institute court action against those with considerable equity. Mr. Adams, on the other hand, advised the settlers not to accept "plan W." His reasons were as follows:

I am convinced that \$375,000 is too large a sum to expect the colonists to pay because, to my satisfaction, it is provable that the settlers cannot pay that much. I am convinced that \$375,000 is too much because if that be the state's final demand at least 25 per cent of the settlers, and possibly 50 per cent, will be forced to vacate either immediately, or within one year.

Based upon the knowledge of the situation in Delhi which I have been able to acquire by first listening to the explanation of their individual cases to me and then by questioning a very considerable number of the colonists, I make the tentative conclusion that a figure just one-half the present figure of \$375,000 could not possibly be far from the correct amount to propose and to undertake to convince the State that it should ask in lieu of the present amount.

That sum [\$375,000] means neither a settlement nor an adjustment to the sense of fullness contemplated by the state as I understood that contemplation last spring. It means neither a fair settlement nor a defensible one. On the contrary it means ruin for a large percentage

<sup>21</sup> Cleary, C. W. Circular letter. January 9, 1930. (Mimeographed; in files of Giannini Foundation.)

<sup>22</sup> Also see: Anonymous. Thursday, last day for acceptance of plan "W" according to C. W. Cleary. *Delhi Record* 6(52):1. January 31, 1930.

<sup>23</sup> <sup>24</sup> Anonymous. Plan "W" is accepted. *Delhi Record* 7(1):1. February 7, 1930.

<sup>25</sup> Anonymous. Opposers of plan "W" to meet with State Land Settlement Board in Governor's chamber at Sacramento this morning at ten o'clock. *Delhi Record* 7(2):1. February 14, 1930.

<sup>26</sup> See various items in: *Delhi Record* 7(2):1. February 14, 1930.

of Delhi families, who, under differing conditions which I feel we have a right to ask, would remain successfully and happily on their home places. It means justification on the part of many settlers to institute litigation against the state. It means three classifications of Delhi settlers rather than one. Those three are, first, those to whom this adjustment is agreeable and just; second, those to whom it offers some faint glimmer of hope only and who therefore might reluctantly accept it rather than face the terms of their old contracts and, third, those to whom it can mean nothing but immediate ejectment.

If I am correct in my judgment that in the second and third classes will be found far more than half the people of Delhi, then that is all the proof that any reasonable man could ask that this adjustment is not a proper and adequate one.<sup>205</sup>

The opposition to "plan W" was too strong and a new committee was appointed composed of the old Settlers' Executive Committee and of opponents, with Mr. Adams as head. It was insisted that those who had already accepted "plan W" would not be discriminated against in a more liberal adjustment. Mr. Adams then got in touch with every settler and worked out individual agreements with each one.<sup>206</sup>

In working out these individual agreements Mr. Adams was unable to maintain equity as between the settlers. He described the adjustment as follows:

The mistakes in my plan, which we may term inequalities, in some cases at least were necessary to secure signatures. Others were wholly unintentional. On the whole they are more glaring than I had suspected. But the fact that they are glaring is not now, nor never could be, a subject for successful criticism from any source which would rate sufficient for us to risk failure of the whole withdrawal undertaking at this time to forestall. Policy, covering a wide range, is still the paramount motive for concluding the negotiations on the basis I have proposed and policy remains the conclusive reason why, just and fair and defensible as your revisions are, those revisions should not even be proposed at Delhi, let alone attempted.<sup>207</sup>

The state officials described the situation as follows:

The board, while recognizing the inequities, as between individual settlers, in the Adams figures and the general fact that the settlers were receiving thereunder larger adjustment credits, in many instances, than in equity they were entitled to receive, nevertheless, after due consideration, concluded that absolute equity could never be accomplished; that it was apparent that the settler least favorably affected by the Adams figures was nevertheless receiving a generously adequate adjustment; and that an adjustment on the basis of the Adams figures was preferable to continued proprietorship by the State, . . .<sup>208</sup>

A great deal of criticism has been given to the part played by the veterans in the settlement at Delhi. The state officers who worked out the final settlement made the following statement regarding the veterans.

Records indicate that this group of settlers was a source of trouble from the start and there

<sup>205</sup> Adams, E. G. [Speech given at meeting of Delhi settlers. January 23, 1930.] In: Opposers of plan W ask state to postpone action for sixty days. *Delhi Record* 6(51):1. January 24, 1930.

<sup>206</sup> Anonymous. New plan of settlement offered. *Delhi Record* 7(6):1. March 14, 1930.

Anonymous. State will withdraw from land settlement. *Delhi Record* 7(17):1. May 30, 1930.

California Department of Agriculture, Division of Land Settlement. Final Report. June 30, 1931. *op. cit.* p. 21-24. (Appendix A. Summary of provisions of state land settlement readjustment plans as amended May 28, 1930, and finally approved by the State Land Settlement Board pursuant to Chapter 352, Statutes 1929.)

<sup>207</sup> Adams, E. G. Letter to C. W. Cleary. Printed in: California Department of Agriculture, Division of Land Settlement. Final Report. June 30, 1931. *op. cit.* p. 18.

<sup>208</sup> California Department of Agriculture, Division of Land Settlement. Final Report. June 30, 1931. *op. cit.* p. 13.

were fourteen of them still in the colony when the present readjustment was undertaken. In connection with the adjustment and all attempts to work out a program the presence of these disabled veterans as settlers worked eternally against a reasonable basis of adjustment, though some individuals in the group were very reasonable and fair in their attitude toward the State.<sup>299</sup>

As a group the disabled veterans seem to have received the best deal. Under "plan W" they would still have owed \$59,872. Under the final adjustment they received a net credit of \$2,443. They had great political power, and as individuals, they had an assurance that other settlers lacked. Their attitude, however, was not peculiar to them. Any difference that existed was one of degree. This fact was shown abundantly by the parallel experience at Durham, where there was only 1 or 2 veterans. When the proportion of extremists among the veterans as a whole is compared with the extremists among the others, there is little difference. For instance, 42 out of 68 veterans accepted "plan W," about the same ratio as was found among the rest of the settlers. Most of the settlers became hard to deal with. It seemed to some critics that, as Americans, they were inherently antagonistic to governmental supervision and control.

#### THE DELHI ADJUSTMENT

Since the agreement effected was based on individual circumstances, with no exact application of any formula, only a few specific details can be given. This adjustment, of course, was in addition to the 1925 adjustment. In the final adjustment the settlers on laborers' allotments had their debts reduced on the average from \$969 to \$44; those on poultry farms from \$2,198 to \$272; those on the larger farms from \$8,802 to \$1,111. Fifty-nine settlers received credit balances totaling \$40,078. Fourteen received over \$1,000 in cash each besides the deeds to their farms. One man received nearly \$5,000 in cash. The state not only allowed these credits but, under certain conditions, bought back the farms at the new valuation less the amount still due the state. Under this arrangement 22 settlers sold their farms to the state, and 7 more made trades for other property.<sup>300</sup>

Before the final adjustment at Delhi, a special agreement had to be worked out with the Federal Land Bank at Berkeley and with the Delhi National Farm Loan Association; the settlers had failed to meet their payments on many properties on which the bank had placed loans, and those who were members of the Association were liable up to 10 per cent of their own loans for any losses to the bank. The settlers consequently required the state to reimburse the bank so that no later claim would be placed against them. The arrangement worked out with the bank and the Association was as follows:

In the process of adjustment with the purchasers of Delhi properties in 1930 and prior thereto, 32 pieces of property, aggregating 915 acres, reverted to the State subject to first mortgages of the Federal Land Bank of Berkeley. It became apparent that it would be impossible to dispose of these properties for even enough to pay the obligations against them and as there was not sufficient in the land settlement fund to meet the regular semi-annual payments to the Bank or the irrigation taxes and as the rental incomes were not enough to meet these obligations, arrangements were made to transfer these properties to the Federal Land Bank.

<sup>299</sup> *Ibid.* p. 14.

<sup>300</sup> Smith, J. Winter. Final Report. [Final adjustment figures as of May 1, 1930.] (Type-written; in files of California Department of Finance, Division of State Lands.)

.... upon the sale of these properties the obligations to the Federal Land Bank of Berkeley would be reduced to amounts reasonably believed to be low enough to protect the Association's membership from possible loss. As there were no funds available in the land settlement fund to reduce the obligations in the amount agreed upon, arrangements were made to transfer to the Federal Land Bank promissory notes secured by trust deeds held by the State on properties in the Delhi State Land Settlement at the face value of \$18,583.00, the amount of difference at the time of transfer. The State also transferred an additional number of such securities at the face value of \$13,992.00.<sup>301</sup>

TABLE 10

## FINANCIAL STATEMENT OF DELHI STATE LAND SETTLEMENT, JUNE 30, 1931

<i>Assets:</i>	
Available funds . . . . .	\$ 11,872.47
Deferred indebtedness . . . . .	77,177.62
Unsold land . . . . .	298,978.00
Miscellaneous . . . . .	18,081.12
Total assets . . . . .	406,109.21
Deficit . . . . .	2,097,520.80*
	\$2,503,630.01
<i>Liabilities:</i>	
Total . . . . .	\$2,503,650.01

\* Deficit includes \$127,819.59 accrued interest due the general fund from the Land Settlement Fund.

## Source of data:

California Department of Agriculture, Division of Land Settlement. Final Report, June 30, 1931. *op. cit.* p. 25.

This additional transfer was stated to be in consideration of: accrued interest on loans against properties; first installment, Turlock Irrigation District taxes, assessed against properties for fiscal year 1932-33; maximum liability of state by virtue of stock issued by Delhi National Farm Loan Association at time loans were made on properties; abstract of titles to properties; and reserve for losses on account of failure of promisors of promissory notes secured by deeds of trust on real properties to meet principal and interest payments. This arrangement with its security transfers reveals the low value placed on Delhi land and the ingenuity required to effect a settlement.

## THE DURHAM ADJUSTMENT

The settlers at Durham who were included in the general adjustment plan were those on the better soils and who owned 3,546 acres. Most of the adobe and pasture lands had been taken back by the state and were sold outright. The water rights originally given with the adobe lands were kept by the state and distributed among the owners of the better soils. These settlers on June 30, 1928, which was the date on which the adjustments were figured, owed the state \$485,086. They were granted credits totaling \$371,028, which left a net debt of \$114,058. Forty-one settlers received balances aggregating \$40,469. Part of the adjustment was based on a revaluation of the land and started with a minimum reduction of 50 per cent of the original sale price. The adjustment

<sup>301</sup> California Department of Finance, Division of State Lands. [Report to the Governor and the Legislature on status of disposal of settlement lands.] January 26, 1935. p. 6. (Type-written; in files of Giannini Foundation.)

in many cases allowed an additional reduction in order to compensate for damages from the irrigation system.<sup>202</sup>

#### FINANCIAL RESULT FOR THE STATE

Tables 10 and 11 are summaries of the final financial statements of the two settlements. They show a deficit of \$427,995.59 for Durham and of \$2,097,-520.80 for Delhi. This plus the \$350,000 interest remission in 1925 for Delhi approximates the loss sustained by the state up to the final agreement. Since most of the agreements were settled early in 1930 and were based on valuations made early in 1929, these losses were, of course, due in very little part to the depression which began in 1929.

TABLE 11  
FINANCIAL STATEMENT OF DURHAM STATE LAND SETTLEMENT, JUNE 30, 1931

<i>Assets:</i>	
Available funds .....	\$ 7,973.07
Deferred indebtedness .. . . . .	121,946.15
Delinquent indebtedness .. . . . .	1,433.29
Farm allotments unsold .. . . . .	54,421.60
Improvements on same .. . . . .	2,250.00
Miscellaneous .. . . . .	4,554.67
Total assets .. . . . .	192,578.78
Deficit .. . . . .	427,995.59*
	\$620,574.37
<i>Liabilities:</i>	
Total .. . . . .	\$620,574.37

\* Deficit includes \$66,365.53 interest due the general fund of the state from the Land Settlement Fund.

Source of data:  
California Department of Agriculture, Division of Land Settlement. Final Report. June 30, 1931. *op. cit.* p. 25.

Some additional losses were incurred in liquidating the remaining assets of the state and were in part due to the depression which followed 1929. By 1935 the Durham books had been cleared of all but \$600 of the deferred indebtedness, which, plus interest, had once had a book value of \$130,002.36 but for which the state received only \$82,850.33, a loss of \$47,152.03.<sup>203</sup> The farm sales recorded show that for land valued at \$44,700.25 at the final adjustment, the state received \$26,065.53, or a loss of \$18,634.72. At Delhi \$35,311.41 of the deferred indebtedness was liquidated for \$30,564.20, and 793 acres traded at a valuation of \$36,953.50.<sup>204</sup>

#### CONCLUSIONS

A review of the California State Land Settlements at Durham and Delhi is fraught with difficulties. Not only were there numerous and various factors involved in the situation that came to prevail at the settlements but they were

<sup>202</sup> California Department of Agriculture, Division of Land Settlement. Final Report. June 30, 1931. *op. cit.* p. 16.

<sup>203</sup> California Department of Finance, Division of State Lands. [Report to the Governor and the Legislature on status of disposal of settlement lands.] January 26, 1935. *op. cit.* p. 1-10 and exhibits A to C-1.

<sup>204</sup> California Department of Finance, Division of State Lands. [Supplementary report to the Governor and Legislature on status of disposal of settlement lands.] April 30, 1935. p. 1-3 and exhibits A to C. (Typewritten; in files of Giannini Foundation.)

complex and often indeterminate. There were divergent viewpoints and bitter conflicts among the people involved. These attitudes, however, although ever present in later years, had little to do with the initial failure; neither groups nor personalities brought about the results obtained; rather the California State Land Settlement Board was defeated by unfeeling and relentless physical facts.

#### THE CAUSES OF FAILURE

*Crop Failures.*—Durham and Delhi failed primarily because the high-income crops, for which both settlements had been planned, failed. These failures necessitated the growing of low-income crops for which the original purchase prices and costs of development were too high and for which the individual farms were too small for profitable farming. The crop losses, moreover, were due to physical and biological factors which in the main were not subject to correction. Crops failed regardless of the care given them. The proponents of state land settlement had believed that by the provision of liberal credits, by the use of trained agriculturists, and by proper colonizing methods and procedures, the state would be able to colonize successfully. The program, however, regardless of its character, was of no avail at Durham and Delhi because the poor soil and the high costs of development could not be corrected and farming could not be made profitable under such circumstances.

*Appraisals and Planning.*—The reason that poor land was purchased and that too high a price was paid rests in part on the inevitable chance that is always existent in the purchase and development of land, in part on the character of the appraisals, and in part on the lack of better choices. It now appears that serious risks were taken at the times when the two tracts were purchased. While some of the factors which caused failure were unknown, others were known; their significance was simply not realized. In part this seems to have been due to the fact that the Board's own detailed soil surveys, the special crop analyses, the detailed estimates of costs, and the farm-management plans were made after the purchases had been made. Those making detailed studies were seriously handicapped in such circumstances. Since they made their studies after the Board was committed to buy these tracts at high prices, they were logically excluded from giving attention either to feasibility or to the alternative of low-income crops. The desirability of making and examining detailed plans before deciding on the feasibility of a project seems to have been demonstrated.

*Lack of Suitable Land.*—A great many people have claimed that other tracts should have been selected; probably one or two other tracts would have served better. In the light of the information obtained or obtainable at the time of purchase, however, the choices made appear reasonable, if one assumes that a tract had to be purchased. The significant feature is that so few tracts were found that were worth considering. The proponents of land settlement had believed that millions of acres of land were available; yet the Board had few worth-while tracts to select from, and the ones which they thought were the best, turned out to be unsuitable. It must be emphasized that this unsuitability of the available land was due to physical factors, factors not susceptible to correction. As far as group settlement of tracts several thousand acres in size is concerned, it seems apparent that the State Land Settlement

Board encountered a fundamental limiting factor. The situation may also be regarded as of a permanent character except where technical or economic changes have occurred sufficiently important to overcome the disadvantages that existed.

*Price Fluctuations.*—There were, of course, factors other than poor land which contributed to the failures. At the time the Delhi and Durham tracts were purchased, price relations were favorable to agriculture and expansion seemed to be desirable and profitable. The opposite situation prevailed during the twenties and was unfavorable to development. It is apparent, however, that the statement sometimes made that economic changes and price fluctuation caused the failure of the settlements cannot be sustained. It has been shown that although the prices of labor and materials for construction at Durham were higher than anticipated, the settlers there were partially compensated by higher farm-produce prices. The Board, furthermore, had its extra expenses there much more than offset by the experience at Delhi, where prices of labor and materials were lower than at the time the land was purchased and where much more construction was required. Changes in prices of products sold were unfavorable but were not of first importance so far as cash income was concerned because of the lack of produce to sell. Psychologically it was discouraging, although at Delhi most settlers arrived after prices dropped. Price changes somewhat reduced interest in buying land, yet sales continued and land prices were largely sustained in adjacent areas. When compared with the almost complete loss of intensive crops, price fluctuations cannot be considered of dominant importance in the failures.

*Credit.*—While it has been claimed that the existent credit shortage prevented many settlers from achieving success, this has not been found to be generally true. While money was lacking to develop more farms, enough money was spent on most of the occupied farms to have developed them successfully, if the soil had been productive. The statistics on alfalfa, trees, and dairies, with the accompanying accumulation of investments, are very good proof that capital was adequate. In fact, credit might have been husbanded to advantage at Durham. Farms were improved for one enterprise, such as dairying, and then shifted to another, such as fruit. A number of expensive but little-used buildings were erected. The only inadequacy of capital was also at Durham where it may have prevented an attempt to drain the land. Even in this instance funds were probably available at one time; the Board spent them at Delhi rather than at Durham. No provision, moreover, seems to have been made by which any such expenditures could have been charged to the settlers.

It is sometimes claimed that the Board's policy of loaning up to 95 per cent of the value of the land and up to 60 per cent of the value of improvements so loaded the settlers with debt that they could not pay out and hence was a cause of failure. No important difference has been noted between those who borrowed the maximum amount and those who borrowed less; they all had comparable claims against the state. Those who borrowed heavily were perhaps more extreme in their demands, but the state's liberal collection and adjustment policies obliterated differences which otherwise might have existed.

It is true that a settler with a large equity and a small loan could repay easier and could sustain losses better. The total losses to society, however,

would be the same, and it is the total return on total investment that must be considered in examining the success of an enterprise. From the viewpoint of planning, the settler was just as entitled to a return on his own investment as he was obligated to make a return on borrowed funds.

*Settlers.*—The settlers have often been charged with incompetence and the point made that they themselves brought about failure. In reality, almost all the settlers at Durham and a large number of those at Delhi, were as capable as could be expected. Significantly, crops failed regardless of individual abilities. The settlers have also been charged with unwarranted antagonism to the state's program. While later they became difficult to deal with, in the first years when success seemed possible, they were very coöperative. The change in attitude is to be attributed to lack of income, in turn due to poor crops. It is difficult to overemphasize the effect of a crop loss on a farmer; the rapidly mounting delinquencies must have been discouraging.

*Administration.*—In the administration of the program the officials have been accused of inexperience, poor judgment, extravagance, and even fraud. The evidence for these charges has been carefully examined. The officers' correspondence has been read, office records have been searched, reports of auditors and special investigators studied, and interviews obtained with most of the people concerned. No fraud has ever been proved. Some of the staff lacked experience when they took over their duties, but they soon compensated for this lack by application and willingness to learn. Engineers seem to agree that in general the projects were well designed and executed. The important exception was the interference with natural drains at Durham. Expenses were much higher than anticipated and thus provide the reason for the charge of extravagance. The reason for high costs at Durham, however, was the increase in prices. High costs were inevitable at Delhi. They were unexpected because of inadequate estimating.

The administration of Governor Richardson and Mr. Wooster has been accused of wrecking the settlements but there is nothing to substantiate the charge. Delhi was bankrupt and Durham probably so before the change in administration. More capital for further development at Delhi was not available under Governor Richardson, but since many farms already piped lacked settlers, any expenditure on more farms would have been to no purpose. The loss of construction jobs and the end of liberal loans were severe blows to that community's morale but such credit as was provided served largely as temporary relief.

*Governmental Control.*—It is maintained by some that the settlements failed because they were under state management. Such was not the case because the important causes of failure would have operated regardless of the auspices. Only in indirect ways and for a limited number of settlers can government control be held to be a cause of failure. If private parties had made the subdivision, probably collections might have been more stringent. This in turn might have forced some settlers to use greater effort. It seems more probable, however, that under such auspices more settlers would have accepted their losses and left the settlements. The settlers would have had no hope of recompense from private subdividers as they had from the state. Consequently the settlements might not have been developed to the extent they were.

**THE DISTRIBUTION OF LOSSES**

This hope of recompense was a most important element in the final agreement by which the state withdrew from participation in the settlements. It encouraged the settlers to make their original demands and eventually to force the state to accept almost all losses involved. A number of factors operated to the benefit of the settlers in this matter. The collection policy pursued by the various administrations taught the settlers that an amount due and delinquent did not affect their status. The construction and operation of the irrigation system put the state in a very vulnerable position; its obligation to operate the system became more important than the settlers' obligation to pay their debts. The group nature of the settlements enabled the settlers to bring strong political pressure to bear on the administration. The "promises" of the Board and its officers led the settlers to believe that the state would be responsible for success. While fraud and misrepresentation were not established and while the obligations which a state assumes when it embarks on such an enterprise are not at all susceptible to exact definition, one point was clearly evident at Delhi and Durham: settlers, juries, public, and administration alike did not accept as final the contractual relations that existed between the state as creditor and the settlers as debtors. This point, in conjunction with the responsibilities assumed under the Board's policy of aid and direction, led the state to accept the burden of losses that was sustained.

# H I L G A R D I A

*A Journal of Agricultural Science Published by  
the California Agricultural Experiment Station*

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VOL. 15

FEBRUARY, 1944

No. 6

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## COMPOSITION AND QUALITY OF MUSTS AND WINES OF CALIFORNIA GRAPES<sup>1</sup>

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### INTRODUCTION

THE UTILITY of a given variety of grapes for wine making depends upon several factors. These include production factors such as scion-stock interrelationship, susceptibility to disease, inherent vigor of the vine, resistance to frost (which depends on the time of leafing out, the vine's ability to produce crops after frost injury, and the like), and the yield and composition of the grapes under various soil and climatic conditions. One must also carefully evaluate: (1) the influence of environmental conditions (rainfall, wind, fogs, humidity, exposure, mean daily temperature, and time of maturity); (2) the adaptability of the must to various vinification and amelioration practices (temperature, type of yeast, aeration, and other variations); (3) the suitability of the wine for aging in the wood and in the bottle (rate of clarification, bouquet development, and resistance to disease); and (4) the basic quality of the wine produced by the variety. The production of wine may be considered as the complex interrelation, interaction, and mutual influence of all these factors with and upon each other. In order to study wine-grape-variety adaptation in California, one must consider each of these critically and separately.

The primary problem in enology is to determine the influences which affect the quality of a wine. Since grapes are the raw material, a study of the various varieties is the starting point. Because of the numerous variations in environmental conditions in California, the experiments must be repeated with each variety in as many different localities as possible.

Several previous studies and publications have been devoted to the wine-grape variety situation in California. Haraszthy's importations in 1860<sup>4,5</sup> and

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<sup>4</sup> Haraszthy, Agoston. Report of the commissioners on the culture of the grapevine. Appendix to Senate and Assembly journals. Vol. III, 13th Session, 1862. 30 p. State Printing Office, Sacramento, Calif. 1862.

<sup>5</sup> Arpad Haraszthy reported in 1888 (*Annual Report of the Board of State Viticultural Commissioners for 1887*, p. 7, State Printing Office, Sacramento, Calif., 1888) that there were 200,000 cuttings and rooted vines in Agoston Haraszthy's importation of 1862. Charles Wetmore in 1880 (*First Annual Report of the Board of State Viticultural Commissioners*, 66 + 91 p., see especially p. 48, Edward Bosqui and Co., San Francisco, 1881) reports: "The collection [of varieties] made by Col. Agoston [sic] Haraszthy has not been preserved; the names of varieties have been confounded in many cases; and there is now a pressing need for a new and complete collection."

those of numerous private individuals<sup>6</sup> had brought many varieties into the state before 1880. Even before this latter date the University of California had begun to view the viticulture industry with special consideration.

*Hilgard's Work.*—Dean Hilgard, in his report<sup>7</sup> as the Professor of Agriculture to the President of the University, remarked in 1879 that the industry was improving because of the introduction of varieties better than the previously used Mission and because of the adaptation of better methods of vinification to California conditions.<sup>8</sup>

The real beginning of the work of the University on wine-grape varieties began in the fall of 1880, when the Legislature appropriated \$3,000 for enological work at Berkeley.<sup>9</sup> A 20 by 46 foot brick cellar was constructed on the campus. Professor Hilgard was in charge of the experiments. His report for 1880<sup>10</sup> summarizes his aims and purposes:

Included in this report were analyses of eleven musts of five common varieties of grapes, including the Mission and Zinfandel, the two most important in this state at the time.

Another report was made in 1882, based on the vintage of 1881.<sup>11</sup> A few more musts of common varieties were made into wine at Berkeley, and tasting of the wines produced had begun.

<sup>6</sup> Leggett, Herbert B. The early history of wine production in California. Thesis for the degree of Master of Arts, University of California. 1939. Copy on file in the University of California Library, Berkeley. Mimeographed copy distributed by the Wine Institute, San Francisco.

<sup>7</sup> Hilgard, E. W. Report of the Professor of Agriculture to the President of the University. University of California, College of Agriculture. Supplement to the Biennial Report of the Board of Regents. 113 p. (See Part VI. Viticulture, p. 61-68.) State Printing Office, Sacramento, Calif. 1879.

<sup>8</sup> Even at this early date, Hilgard was not unmindful of the climatic handicaps of California, since he writes in the report. "I have heretofore suggested that this peculiarity (high alcohol and less acid) might, in a measure, be modified by not allowing the grape to become as 'dead ripe' as is usually done. This would tend to increase the acid at the expense of the sugar, which is in excess at best, thus producing the excessive headiness for which California wines are thus far noted. The vintners object to this course on the ground of the European precedent, according to which every additional day of sun is accounted so much gain to the quality of the wine. But what is true in the cloudy climate of Europe is not, therefore, necessarily true in sunny California."

This advice is still timely, and consistent neglect of the importance of harvesting at the proper stage of maturity causes many of the ills of California wines.

<sup>9</sup> The Board of State Viticultural Commissioners came into existence by the same act of the Legislature, receiving \$4,000 for their work.

<sup>10</sup> Hilgard, E. W. Report of the professor in charge to the Board of Regents. University of California, College of Agriculture. 108 p. (See viticultural appendices no. 8, p. 83-91.) State Printing Office, Sacramento, Calif. 1880.

The plan adopted in this matter is in conformity with my view, expressed in my previous report, and shared by the best vintners in the state, viz.: that among the first necessities of the present situation of California wines in the world's market is the establishment of more definite qualities and brands, resulting from a definite knowledge of the qualities of each of the prominent grape varieties, and of their influence upon the kind and quality of the wine, in blending before, or as the case may be, after fermentation; of the treatment required by each in the cellar, during the time of ripening; and finally, of the differences caused by difference of location, climate, etc., as well as by different treatments of the vines themselves.

<sup>11</sup> Hilgard, E. W. Report of professor in charge to the President, University of California. (See appendix 4. Report of work done in viticultural laboratory with record and discussion of results, p. 122-70.) State Printing Office, Sacramento, Calif. 1882.

No further summary was published until 1886,<sup>12</sup> although in the meantime several bulletins on the wine-grape studies were issued.<sup>13</sup>

In the 1886 report can be noted the beginnings of a system of classifying the grapes being studied. This classification continued in the reports for another twelve years. Briefly, it was based on the geographical origin of the grapes—that is, an arrangement of varieties according to the district abroad where they were best known. Another development noted in this report is the establishment of test blocks. In an analysis of the factors influencing the quality of California wines made for the State Viticultural Commission in 1885 and reproduced in the 1886 report, Hilgard clearly states (p. 41) the interrelations existing between the intrinsic quality of a grape and the care that must be exercised in excluding unsound grapes from the crusher, preventing excessive fermentation temperatures, and preventing undue access of air.

If what I have stated at the beginning of this report be admitted, viz.: that the wines of California must in the main seek their market outside of the State, and must therefore be adapted to shipment to long distances; then it follows that, if we adopt the wine-making processes of southern France, Portugal, and Italy, we must adopt the all but universal practice of fortifying export wines. If, on the contrary, we wish, in our climate, to produce also wines similar to those of Bordeaux and northward to the Moselle, we must of necessity so vary our practice that with grapes of a more or less southern character we may nevertheless be able to impart the characters of the cooler climates to our products. To this end we must distinctly deviate, in some respects, from the exact practice of either the southern or northern region of Europe.

Our wine-makers should be made to distinctly understand these differences, arising from the management of fermentation nearly as much as from the character of the grapes used. While some of these latter, as, e.g., the Malvoisie, cannot safely form an ingredient of any dry wine, and others, like the Burger, and apparently the Mondeuse, will stand unharmed any reasonable amount of stress; yet the great majority will depend upon their mode of fermentation for their claim to greater or less stability under favorable influences; and hence the destination of the product should be definitely considered when handling it. Of the numerous grape varieties now being naturalized in California, from all parts of the earth's vine-growing belt, each one yields its commercially known product not merely by virtue of its intrinsic qualities, but largely as the result of certain methods of treatment to which it is habitually subjected, and among which the mode of fermentation is doubtless the most important. Southern countries have, by a natural process of selection, adopted those varieties which yield desirable results with the rapid fermentation, which is the natural outcome of the high temperature prevailing at the vintage season; while northern countries, as naturally, have chosen prevalently those grape varieties that yield the best results under slow fermentation, upon the maintenance of which the peculiarities of their products largely depend. If then, we desire to reproduce the wines of other countries exactly, we must adopt not only their grape varieties, but also their methods of treatment in fermentation espec-

<sup>12</sup> Hilgard, E. W. Report of the viticultural work during the seasons 1883-4 and 1884-5, being appendix no. IV to the report for the year 1884. With notes regarding the vintage of 1885-6. University of California, College of Agriculture. 210 p. State Printing Office, Sacramento, Calif. 1886.

<sup>13</sup> Hilgard, E. W. Comparative examination of claret grapes from Fresno and Livermore Valley. California Agr. Exp. Sta. Bul. 6:1. 1884.

Hilgard, E. W. Examination of Zinfandel wines. California Agr. Exp. Sta. Bul. 9:1. 1884.

Hilgard, E. W. Examination of Zinfandel wines. California Agr. Exp. Sta. Bul. 12:1-4. 1884.

Hilgard, E. W. Examination of red or claret wines from Mr. H. W. Crabb, Oakville, Napa County. California Agr. Exp. Sta. Bul. 13:1. 1884.

Hilgard, E. W. Examination of red wines from Sonoma and Napa counties. California Agr. Exp. Sta. Bul. 21:1. 1885.

Hilgard, E. W. Analyses of Santa Clara Valley red wines. California Agr. Exp. Sta. Bul. 43:1. 1885.

Hilgard, E. W. The wines of 1885. California Agr. Exp. Sta. Bul. 51:1. 1886.

ially. A different treatment may produce wines intrinsically good, but after all, resembling only remotely the type it was intended to duplicate. It will not, then, do to prescribe uniform conditions and methods of fermentation for all alike. When a Riesling must is rushed through a four or five days' fermentation, under the influence of a hot September in the Napa Valley, it is no wonder that its relationship to the produce of Johannisberg is scarcely suspected; while, had the fermentation been carried out in one of the cool, rock cellars, its true nature would as surely have been revealed.

It is clear, then, that our wine-makers must learn to keep clearly in mind, not only the grape variety they have in hand, but also the use they expect to make of it, from the very outset.

Nowadays, however, all fermentations can be conducted under controlled environmental conditions. The rate of fermentation should therefore be a less critical factor. On the other hand, for producing special types of wines important changes may be possible with special fermentation procedures.

A large number of small-scale (5-gallon) experiments were being conducted by the University at this time, although Hilgard indicated that he would have liked to use larger cooperage.<sup>14</sup> Hilgard also demonstrated that such experiments must be conducted by some responsible organization over a period of several years.

The work accomplished in 1880 and 1884 with the limited facilities available induced the State Viticultural Convention held in San Francisco in December, 1884, to request \$10,000 from the State Legislature to further the enological research of the University. This work was to have been under the "joint control" of the Regents and the State Viticultural Commission. Although the proposed dual control did not succeed, the University's work was pushed with renewed vigor under the stimulus of additional funds.

*Bioletti's Work.*—Additional and more complete reports were published four years later,<sup>15</sup> in which Bioletti's name appeared for the first time. Bioletti also helped in the summary report in 1896.<sup>16</sup> He wrote the Experiment Station report of 1897,<sup>17</sup> and later, on his return from South Africa and Europe, published in bulletins 193<sup>18</sup> and 197<sup>19</sup> further summaries of variety recommendations.

Although these early experiments were limited as to districts and varieties, abundant information was collected. The utility of many grape varieties was

<sup>14</sup> He also indicates some of his difficulties: "It is, perhaps, scarcely necessary to state that while, in accordance with the provisions of the law, instruction in the science and art of wine-making is given to those desiring it, yet the wines made or received for examination are rigorously reserved for the purposes defined by the law, and that neither students nor other persons can obtain them for any other purpose. Reports to the contrary that have been circulated, whether by word of mouth, or through the press, are simply and unqualifiedly untrue." This statement also applies to the post-Prohibition experiments.

<sup>15</sup> Hilgard, E. W. Report of the viticultural work during the seasons 1887-89 with data regarding the vintage of 1890. Part I. Red-wine grapes, by L. Paparelli. California Agr. Exp. Sta. Rept. 1892:1-345. State Printing Office, Sacramento, Calif. 1892.

<sup>16</sup> Hilgard, E. W. Report of the viticultural work during the seasons 1887-93, with data regarding the vintages of 1894-95. Part I. a. Red-wine grapes (continued from report of 1892). b. White-wine grapes. c. Raisin and table grapes, by F. T. Bioletti. California Agr. Exp. Sta. Rept. 1896:1-374. State Printing Office, Sacramento, Calif. 1896.

<sup>17</sup> Bioletti, F. T. Memoranda on wine, table, and raisin grapes. Partial report of work of the [California] agricultural experiment stations for the years 1895-96 and 1896-97. 455 p. (See p. 245-53.) University Press, Berkeley, Calif. 1898.

<sup>18</sup> Bioletti, F. T. The best wine grapes for California. California Agr. Exp. Sta. Bul. 193:141-60. 1907.

<sup>19</sup> Bioletti, F. T. Grape culture in California. California Agr. Exp. Sta. Bul. 197:115-60. 1908.

established, and the reports had an important influence in encouraging the planting of better ones. Because of the restrictions in districts and varieties tested, Bioletti was not able to eliminate as many varieties as he probably would have liked to do. Furthermore, the steady demand for ordinary wines led the Experiment Station to investigate methods more than varieties after 1900, and the threat of Prohibition gradually eliminated the wine-grape studies. The data of Hilgard and Bioletti clearly demonstrated the important differences in composition of the grapes that existed between the hot, warm, and cool districts of California. Bioletti's report of 1907 divides the state into coast counties and interior valleys. In the present report this subdivision has been expanded into five climatic zones; and later investigators may make further subdivisions, since the state is amazingly rich in distinct climatic regions.

*Later Work.*—Since 1934 the California Agricultural Experiment Station has again systematically investigated the wine-grape variety problem. Because of marked improvements in facilities, such as transportation, temperature control, and analytical methods, the scope of this research was extended to include typical climatic regions in all parts of the state where grapes are grown, a larger number of varieties, and a more complete sampling of each variety; as well as to enlarge upon and refine the observations and analyses that were made on the musts and wines. As the work has progressed, additional varieties have been established in various localities to further test their adaptation, and other varieties, which have shown promise abroad, have been imported for testing under California conditions.

The data collected on a large number of varieties has very definitely indicated their worth under California conditions. There has been no hesitation in condemning varieties whose basic composition and character do not appear to be useful to the California wine industry. Wherever possible, data previously published by this experiment station and by the United States Department of Agriculture<sup>20, 21, 22</sup> have been utilized in arriving at the final recommendation for the individual varieties. Results with tentative adaptations and probable limitations are also given for a number of varieties that have not been tested under sufficiently varied environmental conditions or that have been only recently introduced.

## METHOD OF PROCEDURE

The experimental procedure used has not differed widely from that followed by Hilgard from 1880 to 1896. The biological controls have been stricter, however, and the chemical and organoleptic tests applied have been more complete.

## COLLECTING SAMPLES

Except for a few samples early in the 1935 season, all grapes tested have been transported to Davis for crushing. These few exceptions were crushed and stemmed at the vineyard. Experience showed, however, that with due

<sup>20</sup> Bigelow, W. D. The composition of American wines. U. S. Dept. Agr. Bur. Chem. Bul. 59:1-76. 1900.

<sup>21</sup> Husman, George C. Testing grape varieties in the vinifera regions of the United States. U. S. Dept. Agr. Bul. 209:1-157. 1915.

<sup>22</sup> Husman, George C. Grape districts and varieties in the United States. U. S. Dept. Agr. Farmers' Bul. 1689:1-32. 1932.

care in picking, grapes could be harvested in the most important districts of the state during the morning and crushed in Davis 24 hours after picking. From 50 to 500 pounds constituted a sample; over 90 per cent weighed at least 100 pounds. These grapes were picked from representative vines of solid blocks or from vines characteristic of the variety where they had to be taken from mixed blocks. Samples were secured from variety collections at Guasti, Delano, Sanger, Lodi, Davis, and Oakville, and from commercial vineyards in other parts of the state. Numerous vineyard owners coöperated in furnishing grape samples. Where experience indicated that testing should be conducted on varieties not previously planted in the district, trial blocks were established.

#### WINE MAKING

*Crushing.*—In 1935 the grapes were crushed between rollers and stemmed by hand. Since then a Garola combined crusher and stemmer has been used. By operating the machine at a high speed and feeding the grapes slowly, it would crush adequately even the thick-skinned varieties such as Palomino. The separation of berries and stems was satisfactory in nearly all varieties.

*Fermentation.*—The crushed, stemmed mass was placed in an open oak fermenting tank. In a few cases with white grapes, or where it was desired to produce a white wine from black grapes, the pressing took place immediately after crushing. Ordinarily, however, the crushed mass was placed in a fermenting tank, a sample of juice withdrawn for analyses, and sulfur dioxide added to the remainder. The sulfur dioxide was used to inhibit the activity of the natural microflora and to permit all samples to start fermentation at approximately the same biological purity. Grapes in sound condition received 50 to 150 parts per million of sulfur dioxide. The pure yeast culture was added shortly afterwards. Fermentations usually started within a few hours. The usual University of California "Burgundy" strain of yeast was used for all fermentations. Other strains might, perhaps, have given better results with particular musts; but the use of one strain insured a uniformity of comparison between wines of the same variety of grapes from different regions.

The fermentation of the pressed white juice and the red wines after sufficient color was extracted was completed in oak containers closed with fermentation traps. Daily records were made of the temperature and Balling readings.

*Must Analyses.*—The sample removed for analysis was allowed to stand until the coarse sediment had settled. It was then pipetted into a cylinder, and a Balling or Brix hydrometer floated in it. In a few cases, notably with American varieties, the thick, high-pectin juice did not settle clear. It had then to be filtered or a drop of clear solution used for a refractometer reading. A sample of the clear juice was titrated with sodium hydroxide to a phenolphthalein end point to measure the acidity. The pH was determined with a quinhydrone electrode or a Beckman pH meter.

*Pressing.*—The white musts were pressed within 12 hours of crushing. Too much tannin was extracted in some of the 1935 experiments by having the juice and skins in contact too long. In later years this fault was eliminated. If the pressing was done immediately after crushing, the yields were reduced.

Red musts were pressed when visual inspection showed sufficient color, by

the fourth to sixth day with most varieties. If the grapes had raisined berries, the pressing was done earlier in order to reduce the extraction of sugar and of raisin flavors. Occasionally fermentations were conducted on the skins for 8 to 12 days.

*Temperature Control.*—Until the 1939 season control of temperature during fermentation was not sufficiently uniform. The 1935 fermentations were conducted in an underground cellar that reached 75° to 80° F. The 1936 to 1938 fermentations were conducted in a shed whose roof was sometimes cooled by sprinklers. A moderate control of the air temperature in the room was maintained. The 1939 to 1941 fermentations were conducted in rooms maintained at 72°; and if the grapes were too warm on delivery, they were cooled to below 70° before crushing. Despite the lack of control in the 1935 to 1938 experiments, the fermentation temperatures exceeded 90° on very few occasions. This was because most of the fermentations were conducted on only about 125 pounds of fruit in 15-gallon containers. The large surface/volume ratio in this case permitted rapid radiation losses from the containers. With slow fermentations the percentage heat loss probably exceeded 50 per cent. Since all varieties from all districts were subjected to approximately the same treatments and temperature conditions, the comparisons remain valid. Daily temperature records were obtained during the fermentations.

*Storage.*—The clear wine was racked off the yeast into full containers within a week of the completion of fermentation (usually about a month after crushing). The wines from 1935 to 1938, inclusive, were stored in an underground cellar whose temperature was 65° to 70° F in the summer and fall and about 60° in the winter and spring. Since May, 1939, the white wines have been aged in a refrigerated cellar at 55°, and the red wines at about 59°.

During the first year of aging the wines were racked two and occasionally three times after being taken to the cellar. Between rackings the ullage of the barrels was replaced with wine of the same lot, which was kept in glass. At the time of each racking the material in glass was racked and mixed with the wine from the wood. The white wines, in 5-gallon containers, were bottled 8 to 12 months after the vintage; while most of the red wines were bottled after 12 to 24 months.

#### CHEMICAL AND ORGANOLEPTIC TESTS

Periodical analyses and tasting of all samples has been followed. The earliest tasting took place before the first of the year following the vintage. Immediately thereafter, all the wines prepared in the preceding vintage were analyzed. Since this procedure has been followed each year, the analytical results are strictly comparable. Re-tastings were made at least once annually of wines which were still improving or which were still in good condition. It is estimated that over 15,000 taste records have been made.

*Chemical Procedures.*—During the midwinter rackings, samples were drawn from each container before racking. The analyses were conducted within 12 hours.\* The analytical procedures were simplified somewhat from the most accurate methods in order to facilitate making the large number of analyses and also because extreme accuracy was unnecessary.

\* The authors wish to thank the following for assistance in carrying out most of the analyses reported here: Frank Bergthold, William Dietrich, Bernard Fries, George Gribkoff, Jack Hagerud, Uriel Nielson, and W. O. Williams.

The wine was brought to a standard temperature (about 63° F), and 100 cc pipetted into an 800-cc Kjeldahl flask. To this, 50 cc of water was added, and nearly 100 cc distilled into a 100-cc volumetric flask. The residue was then washed into a volumetric flask. The distillate was cooled to temperature. The alcohol content was measured with the hydrometer, and in 1935, 1936, and 1937 also with a dipping refractometer; it is reported as per cent by volume in the tables. The residue was used for an extract determination by means of a special 0° to 8° Balling hydrometer. It was also saved for tannin and sugar determinations; those for tannin were made by the Association of Official Agricultural Chemists method,<sup>24</sup> and those for sugar by a modification of Hassid's ferricyanide method.<sup>25</sup> For the iron determination, either the extract or the original wine was used. Iron was determined by the orthophenanthroline colorimetric<sup>26</sup> procedure, care being taken that sufficient hydroxylamine was present.

The original wine was used for pH, color, total, and volatile acid determinations. The pH was measured with a quinhydrone electrode or, in 1939 to 1941, with a glass electrode in a Beckman pH meter. The color was determined both by the Dujardin-Salleron vino-colorimeter and in a color comparator with standard dye solutions.<sup>27</sup> A mixture of Eastman A, B, C dyes has been used for white wines since 1938. It was made as follows: Standard solutions of Eastman A, B, C dyes were prepared by dissolving 500 mg of each in 100 cc of water. Ten cc of the red solution and 5 cc each of the blue and yellow solutions were brought to volume with water in a 300-cc volumetric flask. This solution was stable for several months. The plunger of the colorimeter was set at 3 or 6 mm for the standard. The depth of the plunger in the wine tube was multiplied, respectively, by 600 or 300 to give the relative color value.

The total acidity of white wines was determined by titration with phenolphthalein as an indicator. A 5-cc portion of red wines was titrated to a blue-black, red-black, or green-black color, according to the variety, and then phenolphthalein was added and the titration continued until a reddish tinge could be detected. The acidity is reported as grams tartaric acid per 100 cc, in the tables.

The volatile acid was determined by method II of the Association of Official Agricultural Chemists, using 10 cc of wine and distilling off 100 cc. The distillate was heated to boiling for 20 to 30 seconds to rid it of carbon dioxide and titrated to a phenolphthalein end point.

*Notes on Analyses.*—Occasionally, the fixed acid (total acid minus volatile acid calculated as tartaric) content of the wine was found to be higher than the total acid content of the must. This was contrary to expectations, since no acid was added to the musts. Usually this occurred in musts of high pH and low acidity and may be caused by the activity of acid-forming microorganisms. Other factors which may explain this condition are inadvertent addition

<sup>24</sup> Association of Official Agricultural Chemists. Official and tentative methods of analysis. 5th ed. 757 p. Published by the Association, Washington, D. C. 1940.

<sup>25</sup> In unpublished manuscript by M. A. Amerine.

<sup>26</sup> Saywell, L. G., and B. B. Cunningham. Determination of iron. *Indus. and Engin. Chem., Analyt. ed.* 9:67-69. 1937.

<sup>27</sup> Winkler, A. J., and M. A. Amerine. Color in California wines. I. Methods for measuring color. *Food Res.* 3(4):429-38. 1938.

of excessive sulfur dioxide, errors in titration of the must or wine or both, and sampling errors.

The variable relation of the Balling degree of the musts and the alcohol content of the wines indicates that there is no exact relation between the two, even for musts crushed, pressed, and fermented under conditions as uniform as those used in these experiments. The failure to find a uniform Balling/alcohol ratio is caused by several factors. The original Balling is only an approximate density measurement, since the sample is taken from the freshly crushed grapes. Because of differences in degree of crushing between varieties and between the same variety in different seasons or regions, the amount of free-run juice from the crushed grapes will vary. Uniformity in the Balling-alcohol ratio cannot, therefore, be expected.

*Tasting Procedure.*—Since the purpose of the tasting was to evaluate the varieties of grapes, the scoring was based on the merits and defects of the wine which originated in the grapes, rather than those which might arise from fermentation or aging practices. The tasting sheet and the descriptive terms used for recording the results of the organoleptic examination are given below:

*Appearance.*—This refers to the clarity and freedom from sediment; brilliant, clear, dull, and cloudy indicate increasing opaqueness; maximum score 10.

*Color.*—Hue and amount of color must be appropriate to the type of wine; white wines vary from straw, colorless, yellow, gold, to amber and may have green tint; red wines vary from pink to medium and dark red and may have violet or brown tints; maximum score 10.

*Odors.*—For off smells such as oxidized and hydrogen sulfide, subtract points; the aroma varied from varietal to distinct or simply vinous; bouquet developed in aged wines; delicate, agreeable, clean, fruity, aromatic, cooked, rancio, and flowery were other terms used; maximum score 15.

*Volatile acidity.*—When the volatile acidity was not the result of any varietal defect the maximum number of points (10) were usually given.

*Total acidity.*—Wines which lack acidity taste flat and unpalatable; those with too much taste green, unripe, or acidulous; different types of wines require high or medium acidity and the score varies accordingly; maximum score 10.

*Dryness.*—When the residual sugar of dry table wines is the result of excessive sugar in the grapes, points may be subtracted; sweet dessert types which lack sugar owing to a deficiency in the musts taste thin and points may be subtracted; maximum score 8.

*Body.*—The nonsugar solids chiefly influence the texture; white, dry table wines have extract contents lower than red table wines; watery and thin refer to wines lacking extract; rich, heavy, and robust indicate high extract contents; maximum score 6.

*Taste.*—Only those tastes originating in the grape were noted; these include fruity, fresh, bitter, green, stemmy, moldy, raisin, and alcoholic; maximum score 15.

*Smoothness and astringency.*—These terms are more or less reciprocal and must be appropriate for the type of wine; astringency was chiefly noted in red wines and varied from low to high tannin (below 0.11 to 0.30 per cent tannin); smooth, soft, rounded, slightly rough, rough and harsh were indicated for the smoothness; maximum points 10.

*General quality.*—The proper conformity of the constituents for each type of wine make them taste balanced or harmonious; unbalanced and unharmonious indicate the opposite; wines with simple and uncomplicated flavors are usually obvious and lack character or finesse; the response to aging is also important; maximum score 8.

On the basis of the total score four classes may be established for the different qualities of wines: wines scoring 86 to 100 are from the best varieties after proper aging; those scoring from 78 to 85 are wines of above-average quality and in the text are called quality wines; when the score ranged from 70 to 77 the wines were without particular defect, lacked character, would not respond

to aging, and in the text they are called standard or bulk-quality wines; and wines below 70 had some serious defect. Either table or dessert wines which would markedly improve in quality with aging were considered as quality wines. Common wines are those which because of some inadequacy of the variety do not improve with aging.

*Classification.*—It was very difficult to classify wines according to type. Hilgard's tasting record apparently had no independent classification of types, but relied almost solely on the known district of origin of the variety in Europe. This method appeared somewhat disadvantageous, since it set up *a priori* considerations as to what the quality should be; further, it interposed a conscious or subconscious comparison with wines produced abroad, which would certainly not be judicious. In general in the present study the wines have been tasted blind—that is, without previous identification of variety or of place of origin. For such a tasting, some classification of types was needed. The system used for table wines<sup>28</sup> was as follows:

*Dry red wines with varietal character.*—Distinguishable varietal types such as Zinfandel, Cabernet, Barbera, Muscat, Fresia, native Americans, and the like.

*Dry red wines without distinctive flavor.*—Five empirical types were set up: "red table" for wines of medium body and color, medium or higher acidity, and bottling quality; "high hill" for full-bodied wines with high color and some astringency; "red standard" for sound, ordinary wines not of bottling character; "red ordinary" for wines with some defect; and "pink" (or *rosé*) for wines of medium or low body, medium or higher, acidity, and a light pink color.

*Dry white wines with varietal character.*—These include varietal types such as Riesling, Muscat, Semillon, Sauvignon blanc, Traminer, Chardonnay, Americans such as Catawba and Delaware, and others.

*Dry white wines without distinctive character.*—Three empirical types were set up: "white table" for wines with sufficient character for bottling; "white standard" for sound ordinary wines not of bottling quality; and "white ordinary" for wines with some defect.

*Natural sweet white or red wines.*—These include both wines with a distinguishable varietal character such as Semillon, Muscat, and Sauvignon blanc and wines without a distinctive varietal flavor.

The system used for dessert or aperitif wines was as follows:

*Dry white.*—Wines with a rancio or cooked flavor (California sherry type).

*Sweet red.*—Wines with a distinguishable varietal character such as red muscats, and Zinfandel and wines without distinct flavors.

*Sweet white.*—This includes wines with a varietal flavor such as muscatel and very sweet nondistinctive wines of the Angelica type as well as sweet wines with a rancio flavor.

Although not impractical, this system is not proposed for commercial use; but for experimental tasting it had the merit of freeing the tasters from any preconceived ideals regarding types and quality. A simplified tasting card was used to record the pertinent data after the system had been worked out.<sup>29</sup>

<sup>28</sup> For a more complete discussion of these types of wine and their commercial classification see: Amerine, M. A., and M. A. Joslyn. Commercial production of table wines. California Agr. Exp. Sta. Bul. 639:1-143. 1940.

<sup>29</sup> For a more complete discussion of these types of wine and their commercial classification see: Joslyn, M. A., and M. A. Amerine. Commercial production of dessert wines. California Agr. Exp. Sta. Bul. 651:1-136. 1941.

<sup>30</sup> The authors are indebted to their colleagues for assistance during 1936 to 1938. Mr. E. H. Twight was also a member of the staff during most of this period, and his counsel was helpful.

## INFLUENCE OF ENVIRONMENTAL CONDITIONS

The interrelation of environment and variety is revealed in every recognized type of wine. The relative importance of each as a factor in the production of wines of high quality is debatable, with many salient points on either side. Generally speaking, and because each outstanding table wine type takes its character primarily from a single variety, one is inclined to attribute the principal difference between wine types to the variety used rather than to the region of production. Environment limits grape growing to definite regions on the surface of the earth. It likewise, just as definitely, limits the adaptation of individual varieties to certain areas within these regions. It is this environmental-varietal interrelation that furnishes the bases for distinct wine types in most European countries. The significance of variety in European types indicates the great importance of choosing grapes adapted to the particular environment. The fact that the variety or varieties grown in certain European regions are so perfectly adapted to these regions has made it possible for the wines produced there to establish a worldwide reputation for quality.

## INFLUENCE OF CLIMATE

The experience and research of the European vintners and enologists also afford a fairly definite indication of what climate does to grapes. Climate influences the rates of change in the constituents during development and the composition of the grapes at maturity. Under relatively cool conditions ripening proceeds slowly, and this is favorable for producing dry table wines of quality. These conditions foster the retention of a high degree of acidity, a low pH, and good color (see tables 1 and 2). With most table-wine varieties they bring the aroma and flavoring constituents of the grapes and the precursors of the aroma and flavoring substances of the wines to their highest degree of perfection in the mature fruit. The combination of specific environments with the qualities of the White Riesling, the Pinot noir, the Cabernet Sauvignon, or the like, has made possible the great table wines of the world. If, on the contrary, the varieties lack special character, the most favorable climatic conditions will not make possible the production of quality wines. The table wines of these varieties will be improved because of a better balance of the sugar, acid, tannin, and flavor of the grapes at maturity; but they will still lack the special qualities such as aroma, bouquet, and freshness that are characteristic of high-quality wines.

*Effect on Aroma.*—Under warm climatic conditions the aromatic qualities of the grapes lose some of their delicacy and richness, and the other constituents of the fruit are less well balanced; hence the table wines, even of the best varieties, cannot compare with those of the cooler regions. In the very hot regions where growth and ripening changes proceed with great rapidity, the aroma of most dry-wine varieties is harsh and coarse, and the other components are so poorly balanced that usually only common dry table wines can be made.

*Condition for Dessert Wines.*—The abundance of heat in some regions, which makes them poorly suited to dry wines, makes them ideal for dessert wines such as port, muscatel, and sherry. With abundant heat the varieties

especially suited to the production of such wines attain their most perfect development. Large summations of heat, especially just before and during ripening, favor a high ratio of sugar to acid in the fruit; and the effect of the heat on the aroma is less objectionable than with dry wine.

*Application of Climatic Data*—When accompanied by proper vinification and aging, the variety, through its inherent characteristics such as aroma and

TABLE 1  
INFLUENCE OF REGIONAL CONDITIONS ON THE COMPOSITION OF GRAPES PICKED AT APPROXIMATELY THE SAME STAGE OF MATURITY

Variety	Original Balling degree			Per cent total acid (as tartaric)			pH		
	Fresno	Davis	Bonny Doon	Fresno	Davis	Bonny Doon	Fresno	Davis	Bonny Doon
Alicante Bouschet . . . . .	19.9	19.1		0.63	1.29		3.63	2.95	
Burger . . . . .	17.8	17.6		55	0.81		3.40	3.15	
Cabernet Sauvignon . . . . .	22.9	22.4	20.7	0.65	.67	1.10	3.48	3.63	3.41
Sauvignon vert . . . . .	24.2	24.3	22.4	.44	.57	0.57	3.67	3.81	3.28
Semillon . . . . .	21.0	18.1	24.1	.41	55	0.69	3.42	3.36	3.07
Zinfandel . . . . .	21.0	22.8	24.7	0.55	0.55	1.16	3.51	3.58	3.14

TABLE 2  
INFLUENCE OF REGIONAL CONDITIONS ON THE COLOR OF GRAPES\*

Variety	Average color value† (by vino-colorimeter) in various regions				
	Delano, Fresno	Lodi, Guasti, Davis	Livermore Valley, Apti, Ukiah	Napa Valley, Santa Clara Valley	South Sonoma County, Santa Cruz Mts.
Alicante Bouschet . . . . .	54	47	37	28	17
Carignane . . . . .	89	82	70	48	40
Mataro . . . . .	500	286	200	73	62
Petite Sirah . . . . .	57	50	45	28	20
Zinfandel . . . . .	147	91	75	65	20

\* Data from: Winkler, A. J., and M. A. Amerine. Color in California wines. II Factors influencing color. Food Research 3 (4):439-47. 1939.

† The color value is based on the direct reading so that intensity increases as the figures decrease.

flavoring constituents, determines the type of wine to be produced; whereas the regional conditions, by influencing the sugar-acid ratio, the total acidity, and the tannin content, determine the quality within the type.

To evaluate the influence of environment many varieties have been collected from all the principal grape-growing regions of California. In order to reduce the size of tables and to differentiate among the recommendations, the grape districts of the state have been grouped into five climatic regions. This grouping was based upon temperature differences or more specifically upon the summation of heat as degree-days above 50° F for the period April to October inclusive. (For definition of degree-days see footnote in table 4.) The summa-

tions for the regions are: I, less than 2,500 degree-days; II, 2,501 to 3,000 degree-days; III, 3,001 to 3,500 degree-days; IV, 3,501 to 4,000 degree-days; and V, 4,001 or more degree-days. The localities in each region from which one or more samples have been collected were as follows:

Region I: Napa and Oakville in Napa County; Hollister and San Juan Bautista in San Benito County; Woodside in San Mateo County; Mission San Jose in Alameda County; Saratoga in Santa Clara County; Bonny Doon and Vinehill districts in Santa Cruz County; and Guerneville, Santa Rosa, and Sonoma in Sonoma County.

Region II: Soledad in Monterey County; Rutherford, St. Helena, and Spring Mountain in Napa County; Santa Barbara in Santa Barbara County; Almaden Vineyard, Evergreen, Guadalupe district, and Los Gatos in Santa Clara County; and Glen Ellen in Sonoma County.

TABLE 3  
INFLUENCE OF SEASON ON THE COMPOSITION OF MUST AND WINE;  
AVERAGES FROM ALL REGIONS\*

Variety	Average date of harvesting		Balling degree of the must		Wine					
					Per cent alcohol, by volume		Per cent total acid		Color value† (by vino-colorimeter)	
	1935	1936	1935	1936‡	1935	1936‡	1935	1936	1935	1936
Alicante Bouschet	Oct. 1	Sept. 23	21.7	22.9	10.9	12.3	0.61	0.57	64	63
Burger . . .	Sept. 30	Sept. 19	19.8	19.5	9.6	11.0	.66	.55	..	..
Carignane . . .	Sept. 30	Sept. 19	22.3	23.3	10.9	12.4	.70	.50	27	22
Palomino . . .	Sept. 24	Sept. 30	21.5	22.9	11.0	12.5	.38	.36	..	..
Petite Sirah . .	Sept. 28	Sept. 22	23.2	25.6	11.3	13.9	.67	.56	77	59
Zinfandel . . .	Oct. 1	Sept. 19	24.7	23.9	12.8	13.5	.71	.58	31	19
Average of 240 varieties . . . . .	Sept. 30	Sept. 21	22.1	23.0	11.0	12.2	0.61	0.50	39	33

\* Data from: Winkler, A. J., and M. A. Amerine. What climate does—the relation of weather to the composition of grapes and wine. *The Wine Review* 5 (8): 9-11; (7): 9-11, 10. 1937.

† For color value see footnote to table 2.

‡ The apparent discrepancies in the figures for Balling degree and alcohol in 1936 are the result of raisining in the samples.

Region III: Livermore and Pleasanton in Alameda County; Calpella, Ukiah, and Hopland in Mendocino County; Calistoga in Napa County; Alpine in San Diego County; Templeton in San Luis Obispo County; Loma Prieta in Santa Cruz County; and Alexander Valley, Asti, and Cloverdale in Sonoma County.

Region IV: Guasti in San Bernardino County; Escondido in San Diego County; Acampo, Escalon, Lockeford, Lodi, and Manteca in San Joaquin County; Cordeha in Solano County; Ceres, Hughson, and Vernalis in Stanislaus County; Ojai in Ventura County; and Davis in Yolo County.

Region V: Fresno and Sanger in Fresno County; Madera in Madera County; Arena and Livingston in Merced County; and Trocha in Tulare County.

Some of the locations are, as might be expected, on or near the borderline between regions.

#### INFLUENCE OF SEASONAL CONDITIONS

There is also a seasonal influence that is more or less marked according to the locality of the producing region in the temperate zone. Wines of best quality are usually produced in the hot years of the coolest regions. In the warmer locations the cool years produce the higher-quality wines. Greater and more frequent deviations from the optimum conditions required for maturing

TABLE 4\*  
THE SUMMATION OF TEMPERATURE AS DEGREE-DAYS† ABOVE 50° F FOR SEVERAL TYPICAL GRAPE-PRODUCING AREAS

Region and representative stations	Period, blooming to harvest						Ripening periods						1935	1936	1937	1938	1939	1940	1941	Average
	1835	1936	1937	1938	1939	1940	1941	Average	1935	1936	1937	1938	1939	1940	1941	Average				
I ... { Santa Cruz Santa Rosa	1,750 2,030	2,030 2,330	1,760 2,165	1,360 1,905	1,765 1,990	1,655 1,870	1,740 1,975	1,800 2,035	285 400	400 525	370 410	320 355	435 495	330 380	315 425	335 427				
II ... { San Jose. St. Helena..	2,290 2,290	2,290 2,450	2,290 2,355	2,265 2,375	2,080 2,365	2,145 2,325	2,085 2,344	2,187 410	405 505	525 425	415 440	555 560	400 460	475 476	470 468					
III ... { Livermore... Cloverdale.	2,400 2,690	2,595 2,890	2,590 2,720	2,500 2,655	2,360 2,560	2,390 2,620	2,330 2,565	2,452 2,608	450 495	555 625	540 555	575 615	585 590	532 530	480 555					
IV ... { Davis .. Lodi .. Fontana ..	2,505 2,646 2,670	2,765 2,775 2,820	2,686 2,550 2,690	2,670 2,610 2,990	2,515 2,615 2,815	2,630 2,690 2,775	2,525 2,595 2,655	2,601 2,630 2,775	605 610 690	615 615 710	580 605 715	615 615 750	565 555 740	610 550 655	635 609 665					
V ... { Fresno Bakersfield	2,875 2,875	3,095 3,110	3,115 3,165	3,040 2,995	3,120 3,160	2,835 3,205	3,041 3,185	885 885	1,044 1,070	915 990	915 1,070	835 975	875 915	845 915	775 880					

\* Data calculated from California Section, Climatological Data Reports, U. S. Weather Bureau

† For example, if the mean temperature for a period of five days was 70° F., the summation would be  $(70 - 50) \times 5 = 100$  degree-days.

‡ The period from full bloom until the grapes attained the maturity desirable for dry table wines.

§ The 30-day period preceding the date on which the grapes were normally mature for dry table wines.

of the fruit occur in the coolest regions. For this reason, and because California's present grape acreage is all in the warmer part of the geographic zone adapted to grape production, some producers believe that every year is a "vintage year" in California. If this term simply designates years in which the grapes attain full maturity, such belief is correct. By general usage abroad, however, the term designates instead the years of outstanding quality. To say that the wines of all years are outstanding or superior or even to say that the wines of all years are of equal quality in California is far from the truth.

The figures of table 3 indicate the magnitude of the influence of seasonal conditions. They show that the total acidity and the color were lower in the warmer year—1936. The slightly higher Balling degree of the 1936 fruit does not account for the lower average total acid content; and the color normally increases with an increase in maturity.

These figures deal only with substances that may be readily determined. Experience and tastings indicate, however, that other substances are also affected by changes in the seasons to a recognizable but unknown extent.

#### INFLUENCE OF OTHER FACTORS

Climate includes many factors such as wind, rain, humidity, and temperature. Of these, apparently, temperature is the most important single factor in grape and wine production. It is measured fairly readily, though in actual practice not too accurately. Although climate in general and its influence on the quality of wines are of interest, more complete records are available for the differences in temperature between the seasons of the various regions in California than for the other factors; hence temperature will be used not only to explain further the data of table 3, but also to show the considerable annual variation between the years, from 1935 to 1941, for a number of locations in the state. Table 4 shows the summation of heat above 50° F for two periods in the development of the fruit in each of these years.

#### FACTORS INFLUENCING THE SELECTION OF THE BEST VARIETY

In the final evaluation of a grape variety the first consideration must be the use to which the grape is to be put. No variety that produces wines lacking in character can be recommended for the production of quality wines. For bulk wines adequate consideration should be given to the basic essentials of composition and character; then, in addition, sufficient emphasis must be placed on the production factors. The final selection is thus based on two factors: yield, and quality of the product.

*Production.*—Although the necessity of adequate production is self-evident, it becomes less important as the quality increases. Certain poorly yielding varieties continue, for example, to be widely planted throughout the world because they produce outstanding wines—notably the Cabernet Sauvignon. The amount of crop produced also has a marked influence on the composition of the grapes. In years of light crop or, in general, with vines that have a small number of clusters, the sugar content is greater than normal, and the total acidity is reduced. This, of course, influences the character and type of wine.

High-producing varieties should not be planted in districts where only low

production is possible, nor should low-producing varieties be planted in rich soils; no variety will make a fine wine in such locations. Heavy producers, however, are essential in making cheap bulk-quality wine.

A quality grape variety results from a complex of several production factors. The condition of the grapes at harvest is very important. Varieties which easily become moldy, sunburned, rotten, or which insects attack, are more difficult to pick and to deliver to the winery in a satisfactory condition. Such grapes either contribute undesirable spoilage organisms to the musts or give off-tastes to the wine. These varieties, if black grapes, cannot be used for producing white wine. Diseased fruit is also sometimes high in oxidizing enzymes that discolor the white musts and wines. Yield and the soundness of the fruit must both be considered from the production point of view.

*Composition.*—The chemical composition of the musts is also very important. The sugar/acid relation may apparently take any one of four forms, although for a given variety this is influenced somewhat by amount of crop and various environmental conditions. These four forms are: low sugar with low acid; low sugar with high acid; medium sugar with medium to high acid; and high sugar with low acid. The status of this relation will largely determine whether or not the grape is to be used for table wine or for dessert- or appetizer-wine production. The dry table wines, for example, require grapes of fairly low pH (3.0 to 3.4), high acidity (0.6 to 0.9 per cent), and a moderate sugar content (19° to 23° Balling). The sweet table wines and the dessert and appetizer wines, on the other hand, must be of a higher pH (3.3 to 3.7), medium acidity (0.4 to 0.6 per cent), and more generous sugar content (23° to 29° Balling).

The Balling-acid ratio has also been shown<sup>a</sup> to be of utility in classifying the varieties of wine grapes within a given region. In region IV those with ratios below 28.6, 31.4, and 34.3 at 20°, 22°, and 24° Balling are typical dry table-wine grapes. Varieties with ratios exceeding these figures at the Balling degrees given are typical dessert-wine grapes. Some varieties have a ratio below 28.6 at 20° Balling, but exceed 31.4 and 34.3 at 22° and 24° Balling. These latter should be grown in a cooler location for table wines and a warmer location for dessert wines. About 100 varieties have been tested by this system for Davis conditions. The procedure in making this type of study involves periodic sampling throughout the ripening period. The results are referred to, for region IV conditions, under the varieties being tested.

The importance of a low pH in fermentations of must intended for table wines is well known.<sup>b</sup> The utility of detailed studies of the acids in ripening grapes for differentiating wine-grape varieties has been demonstrated.<sup>c</sup>

Other composition factors are also important. The presence or absence of anthocyanin pigment will determine whether a red wine may be produced. Numerous varieties that have anthocyanin pigments only in the skins may be used, however, for white wines. There appear to be several classes of white wine-grape varieties as far as the color of wine is concerned. Color may, how-

<sup>a</sup> Amerine, M. A., and A. J. Winkler. Maturity studies with California grapes. I. The Balling-acid ratio of wine grapes. *Amer. Soc. Hort. Sci. Proc.* 38:379-87. 1940.

<sup>b</sup> See citation in footnote 28, p. 502.

<sup>c</sup> Amerine, M. A., and A. J. Winkler. Maturity studies with California grapes. II. The titratable acidity, pH, and organic acid content. *Amer. Soc. Hort. Sci. Proc.* 40:818-24. 1942.

ever, be influenced to a considerable extent by the pH and oxidation-reduction potential of the fermenting must and the resulting wine. The general distinction appears to be between the varieties such as Burger, Folle blanche, and certain Rieslings with only a small amount of yellow pigment in their skin and the well-colored varieties such as Semillon and Muscat Canelli.

The tannin content of red varieties is also important. The varieties, with typical examples, may be divided as follows: high color with low tannin (Saint Macaire); high color with high tannin (Salvador); low color with low tannin (Mission and Grenache); and low color with high tannin (Grignolino and Troia de Barletta). The other composition factors such as inherent flavor and the flavor produced in wine making have already been discussed.

*Time of Maturation.*—In cool regions early-ripening varieties are necessary in order to have the fruit ripen properly. With the possible exception of the coolest portion of region I, early-ripening varieties are not essential in California. Early varieties in most regions of the state are at a disadvantage for two reasons. First, they ripen during the hottest period of the year, and their Balling-acid ratio is unduly increased. Second, unless the grower is particularly careful, the grapes will become overripe before the winery is ready to receive them. Furthermore, because the grapes ripen in the hottest part of the year, they become overripe very rapidly. The only possible advantages of such varieties are to prolong the picking season in very large vineyards and to provide high sugar concentration in cool, unfavorable years. The latter is a minor consideration in this state. Varieties such as Chasselas doré, Meunier, and Red Traminer are seldom useful because of their very early ripening.

Late-ripening varieties, on the other hand, are at a distinct disadvantage in regions I and II, where they fail to mature in cool seasons. In regions III, IV, and V they deserve more attention. Their late ripening enables them to escape the severe heat of September. The climate is hot enough, however, so that they mature normally. Since most of the very large vineyards are located in regions IV and V, the planting of such varieties will help to prolong the picking season without permitting the grapes to become overmature. Varieties such as Mission, Tinta Madeira, Raboso Piave, and perhaps Fogaruna should receive more attention because of their late period of ripening.

*Blends.*—The varieties recommended for planting in the various climatic conditions of the state are given in the sections which follow. In early listings in California mixed plantings were recommended. In the present report the recommendations are to keep varieties segregated, to facilitate harvesting and utilization. A given vineyardist in region I may wish to plant one or all of the varieties listed on page 533. In each of the regions varieties are recommended for making quality red or white wines or for making standard red or white wines. The individual grower must determine which type of wine he wishes to produce, or how much of each, and make his selections accordingly.

Some will wish to plant a number of varieties so that several types of wine may be produced or with the idea of blending. Blending may be considered either from the standpoint of the varieties of grapes or of the types of wines. Many useful varieties of grapes are deficient in one or more necessary substances and even varieties which are ordinarily sufficiently well balanced for producing a satisfactory wine will, under some environmental conditions, fail

to attain their normal composition. Deficiencies in color, sugar, or acid content are common examples of this. In addition, certain types of wine require a particularly nice "balance" which is not often achieved from any single variety of grape. Securing the exact balance in a Champagne stock is an example of this. In either case, blending is a desirable and useful procedure. But blending is not a cure-all, and its indiscriminate use will lower the average quality.

TABLE 5  
RELATIVE VALUE OF RED VARIETIES FOR TABLE AND DESSERT WINES

Variety	Relative value for table wine	Relative value for dessert wine	Relative productivity	Type of pruning*
Aleatico .	52	73	Medium	Spur
Alicante Bouschet .	40	40	High	Spur
Barbera .	78		High medium	Spur
Black Malvoisie .		71	High	Spur
Cabernet Sauvignon .	98		Low	Cane and spur
Carignane .	57	56	High	Spur
Charbono. .	59		High medium	Spur
Gamay .	70		Low medium	Spur
Grand noir .	46	61	High	Spur
Grenache .	82	77	High	Spur
Grignolino .	79		Medium	Spur
Gros Mansenc .	72		Low medium	Spur
Mataro .	47	61	High	Spur
Mission .		79	High	Spur
Mondeuse .	67		High	Spur
Nebbiolo .	68		Low medium	Spur
Pagadebito .	49	45	Medium	Spur
Petit Bouschet .	46	61	Medium	Spur
Petite Sirah . . . . .	71	67	High medium	Long Spur
Pinot noir . . . . .	92		Low	Short cane and spur
Pinot Saint George. . . . .	51		Medium	Spur
Refosco . . . . .	65	67	High medium	Spur
Sangiovese. . . . .	68	..	Medium	Spur
Saint Macaire . . . . .	65	..	High medium	Spur
Tannat . . . . .	69		Medium	Cane and spur
Tinta Madeira . . . . .	..	81	High medium	Spur
Trousseau . . . . .		77	High	Spur
Valdepeñas . . . . .	58	57	High	Spur
Zinfandel . . . . .	67	73	High medium	Spur

\* Where cane and spur pruning is mentioned, see the system of pruning indicated for Cabernet Sauvignon, page 553.

of the products of the winery. Varieties which possess no particular merit and which are markedly deficient or overabundant in color or acid had better be discarded, no matter what their production, rather than to try to rectify them with special grapes and special vinification procedures. This is especially true for the ordinary varieties of grapes when acceptable substitutes exist. Likewise, it would frequently be better to leave varietal wine types undiluted and age them longer than to dilute them beyond recognition in order to achieve an early maturity.

*Relative Value of Varieties.*—The two primary objects of this investigation, to date, have been concerned with the influence of region and variety on the quality of the wines produced. The relative importance of the region is definitely shown by tables 8 to 25. Similar information for the varieties is indi-

cated, though not so directly, by the statement regarding the samples from a single region and year at the right of the tables.

The use of numerical equivalents for the relative values of the different varieties makes direct comparisons possible and lends emphasis to their worth for wine production. Such values can be derived directly from the tasting scores of the wines of each variety, since all wines were scored on the same

TABLE 6  
RELATIVE VALUE OF WHITE VARIETIES FOR TABLE AND DESSERT WINES

Variety	Relative value for table wine	Relative value for dessert wine	Relative productivity	Type of pruning*
Burger . . . . .	61	..	High	Spur
Cataratto . . . . .	72	..	High medium	Spur
Chardonnay . . . . .	92	..	Low	Cane and spur
Chasselas doré . . . . .	52	..	Low medium	Spur
Clarette blanche . . . . .	61	..	High	Spur
Fehér Szagos . . . . .	..	57	High	Spur
Folle blanche . . . . .	69	..	Medium	Spur
French Colombard . . . . .	67	..	High	Spur
Gray Riesling . . . . .	47	76	High	Spur
Green Hungarian . . . . .	51	..	High	Spur
Inzolia . . . . .	47	68	High	Spur
Palomino . . . . .	48	82	High	Spur
Pinot blanc . . . . .	83	..	Low	Spur
Peverella . . . . .	77	..	High	Spur
Red Traminer . . . . .	81	..	Low	Cane and spur
Roussette . . . . .	57	..	Medium	Spur
Sauvignon blanc . . . . .	78	..	Low medium	Cane and spur
Sauvignon vert . . . . .	48	61	Medium	Spur
Semillon . . . . .	85	..	Medium	Spur
Saint Emilion . . . . .	67	..	High medium	Spur
Sylvaner . . . . .	85	..	Low medium	Spur
White Riesling . . . . .	88	..	Low	Cane and spur
Muscat of Alexandria . . . . .	41	67	High	Spur
Muscat Canelli . . . . .	68	82	Low medium	Spur
Muscat Hamburg . . . . .	52	67	High	Spur
Malvasia bianca . . . . .	56	73	Medium	Spur
Orange Muscat . . . . .	67	77	High	Spur

\* Where cane and spur pruning is mentioned, see the system of pruning indicated for Cabernet Sauvignon, page 553.

basis and by the same individuals. To do this the average score for each was reduced to a common basis. A value of 40 was arbitrarily assigned to the wines of Alicante Bouschet, which regularly received a low score, and then the numerical equivalents for the other varieties were obtained by using the differences between the average scores of their wines and the score of the wines of Alicante Bouschet and multiplying this by five to secure a proper spread. Any other variety could have been used as a basis for the comparisons as long as an appropriate value was assigned, but the Alicante Bouschet was chosen because it is generally grown and well known. Values for the varieties now grown to a considerable extent as well as the varieties that are recommended for planting are shown in tables 5 and 6. The relative values for the different varieties shown in these two tables are for the region or regions to which the varieties are best adapted for the production of either table or dessert wines.

TABLE 7  
RECOMMENDATIONS FOR WINE TYPES AND REGIONAL ADAPTABILITY OF VARIETIES FULLY TESTED\*

Variety	Type of wine	Region					Remarks
		I	II	III	IV	V	
Aleatico	Red dessert	No	No	No (s)*	Yes (s)*	Yes (s)	Lacks color
	Red table	No	No	No	No	No	Very poor quality
Alicante Bouschet	Red dessert	No	No	No	No	No	Average quality; good color
	White table	-	-	Yes	No (l)	No	Good quality
Alicanté Ganzan	Red table	-	-	No	No	No	Lacks character
Aligote	Red table	-	-	No	No	No	Average quality; good producer
Antibio	Red table	-	-	No	No	No	Poor quality
Aramon	Red table	-	-	No	No	No	Very good quality
Aspirine noir	White table	-	-	No	No	No	Low producer; good quality
Barbera	Red table	-	-	No	No	No	Not suitable for wine
Becchan	Red table	-	-	No	No	No	Average quality
Blauk Hamburg	Dry white dessert	-	-	No	No	No	Better for table grape
Black Malvoisie	Red table or dessert	-	-	No	No	No	Poor quality
Black Prince	Red or white table	-	-	No	No	No	Average quality
Blauke Elbe	Red table	-	-	No	No	No	Unbalanced must
Bolghino	Red table	-	-	No	No	No	Below average quality
Bombino bianca	White table	-	-	No	No	No	Average quality for blending
Bonarda	Red table	-	-	No	No	No	Very good quality
Burger	White table	-	-	No	No	No	Average quality
Cabernet Sauvignon	Red table	-	-	Yes	Yes (s)	Yes (s)	Average quality
Carignane	Bed table or dessert	-	-	No	No (l)	Yes (s)	Poor quality
Chardonnay	Red table	-	-	No	No	No	Excellent quality
Chasselas doré	White table	-	-	Yes	Yes (s)	No	Poor quality
Chauvache noir	Red table	-	-	No (l)	No	No	Poor quality; poor vines
Chenin blanc	Dry or sweet white table	-	-	No	No (l)	No	Average quality
Chennin noir	Pink table	-	-	No	No	No	Poor quality
Clairette blanche	White table	-	-	No	No	No	Average quality
Coristano	White table	-	-	No	No	No	Unbalanced must
Criolla Mossa and Vino	White dessert	-	-	No	No	No	Lack color and quality
Croatto Moretto	Red table or dessert	-	-	No	No	No	Poor quality
Doleatto	Red table	-	-	No	No	No	Poor quality
Early Burgundy	Red table	-	-	No	No	No	Poor quality
Fehler Saeges	White dessert	-	-	No	No	No	Poor quality

\* "No" recommends followed by (l) mean that the variety should be planted in the region only under special circumstances, usually more completely explained in the text. "Yes" followed by (s) indicates that although the quality is only average the variety has special attractions in production, dual utilization, color, flavor, or other properties that merit attention.

Folle blanche.....	White table .....	No	No (t)	No
French Colombard.....	White table .....	No	Yes (s)	No (t)
Froissé.....	Red table .....	No	No (s)	No (t)
Gamay.....	Red table .....	Yes	No (t)	No (t)
Grand noir.....	Red table or dessert .....	No	No (t)	No
Gray Alesing.....	White table or dessert .....	No	No (t)	No (t)
Greco rouge.....	White table .....	No	No	No
Green Hungarian.....	White table .....	No	No	No
Grenache.....	Red table .....	No	No	No
Grignolino.....	Red table or white dessert .....	No	No (t)	Yes
Cross Manzene .....	Pink table .....	No	No	Yes (s)
Groseille bleue.....	Red table .....	No	No	Yes (s)
Hibron blanc.....	White table .....	No	No	No
Hungarian Millennium.....	White dessert .....	No	No	No (t)
Insolis.....	White dessert .....	No	No	Yes (s)
Kedarka.....	Pink table .....	No	No	No
Kleinberger.....	White table .....	No	No (t)	No
Koticha.....	Red table .....	No	No	No
Lagrain.....	Red table .....	No	No	No
Lambrusche Langhe.....	Red table .....	No	No	No (t)
Lenoir .....	Red blending .....	No	No	No
Limbiger.....	Red table .....	No (t)	No	No
Macaroli .....	Pink table .....	No	No (t)	No
Malmezy.....	White dessert .....	No	No	No (t)
Malvasia bianca .....	Muscated .....	No	Yes	Yes
Mammolo Toscano .....	Red table .....	No	No	No (t)
Marsanne .....	White table .....	No	No	No
Maremmino .....	Red table .....	No	No	No
Mataro.....	Red table or dessert .....	No	No	No
Mathiasz y-ne .....	White muscated .....	No	No	No
Mauviere .....	Red table .....	No	No	No
Mission.....	White dessert .....	No	No (t)	Yes (s)
Mondave .....	Red table .....	No	Yes (s)	No
Mourisco branco .....	Dry white dessert .....	No	No	No
Muscatelle.....	Sweet table .....	No	No (t)	No
Muscat Canelli .....	Muscated .....	No	Yes	No
Muscat Hamburg .....	Red muscated .....	No	No	No (t)
Muscat of Alexandria.....	Muscated .....	No	No	No (t)

(Continued on following page)

TABLE 7—(Continued)

Variety	Type of wine	Region I	Region II	Region III	Region IV	Region V	Remarks
Muscat Pantellana.	White muscatal.....	No	No	No	No	No	Ordinary muscat; distinct
Muscat Saint Laurent .....	Muscated.....	No	No	No	No	No	Average quality; weak grower
Nusa Veltliner.....	White dessert.....	No	No	No	No	No	Unbalanced must
Nebbiolo.....	Red table.....	No	No	No	No	No	Average quality
Negreira Gaitanara .....	Red table.....	No	No	No	No	No	Standard red
Negro Amaro.....	Red table.....	No	No	No	No	No	Poor production
Nareitas.....	Red table .....	No	No	No	No	No	Unbalanced must
Nicolas Horthy.....	Muscated.....	No	No	No	No	No	Distinct muscat
Orange Muscat .....	Muscated.....	No	No	No	Yes	Yes	Distinct flavor; average quality
Pagedorito..	Red table or dessert .....	No	No	No	No	No	Very poor wines
Palaverga .....	White dessert .....	No	No	No	No	No	Too neutral
Palomino .....	White dessert .....	No	No	No	No	No	Soft, well-balanced sherry-like
Pavai .....	White dessert.....	No	No	No	No	Yes	Lacks acid and character
Petit Bouschet .....	Red dessert.....	No	No	No	No	No	Very common
Petite Sirah .....	Red table .....	No	Yes	No	No	No	Distinct; slow maturing
Petite Verdot .....	Red table .....	No	No	No	No	No	Low production
Peverella .....	White table .....	No	No	Yes (s)	No	No	Standard, well balanced
Pfeffer .....	Red table .....	No	No	No	No	No	Excellled by other varieties
Piopoule noir .....	Pink table .....	No	No	No	No	No	Too neutral; flat
Pinot blanc .....	White table .....	Yes (s)	Yes (s)	No	No	No	Good quality
Pinot noir .....	Red table .....	Yes	No	No	No	No	For cooler regions only
Pinot Parmand .....	Red table .....	No	No	No	No	No	Poor quality
Pinot Saint George .....	Red table .....	No	No	No	No	No	Lacks acid
Babco Pave .....	Pink table .....	No	No	No	No	No	Latte; good acidity
Red Trainer .....	White table .....	Yes (s)	No	No	No	No	Requires cool climate
Red Veltliner .....	White table .....	No (s)	Yes (s)	No	No	No	Average white
Refozo .....	Red table .....	Yes (s)	Yes	Yes	No	No	Average quality
Roussette .....	White table .....	No	No	No	No	No	Too neutral
Saint Emilion .....	White table .....	No	No	No	No	No	Lacks acidity
Saint Macaire .....	Red table .....	No	No	No	No	Yes (s)	For blending
Salvador .....	Red table or dessert .....	No	No	No	No	Yes	For blending, very dark
Sangiovese .....	Pink-table.....	No	No	No	No	No	Lacks production
Sauvignon blanc .....	Dry or sweet white table .....	No	No	Yes (s)	No	No	Low producer; high quality
Sauvignon vert .....	White table .....	No	No	No	No	No	Poor quality

Selection Carrere	White table	No	No	No	No	No
Semillon	Dry or sweet white table	No (t)	Yes	No (t)	No	Poor quality
Servant	White table	No (t)	No	No	No	Good quality
Steinschiller	White table	..	..	..	..	For blending
Sylvaner	White table	..	..	..	..	Low acid and quality
Tannat	Red table	..	..	..	..	Fruity, soft
Terret	Red table	..	..	..	..	Slow maturing
Tinta amarela	White table	..	..	..	..	Poor quality
Tinta Cao	Red dessert	..	..	..	..	Fruit rots
Tinta Madeira	Red dessert	..	..	..	..	Surpassed by Tinta Madeira
Tronseau	Red table	..	..	..	..	Good quality
Valdepenas	Red dessert	..	..	..	..	Good quality; lacks color
Verdelho	Red table	..	..	..	..	Average quality
Vernentino Favorita	White table or dessert	..	..	..	..	Rich flavor, low producer
Vernacchia bianca	White dessert	..	..	..	..	Possible for sherry
Vernacchia Sarda	White table	..	..	..	..	Little character
White Riesling	White table	..	..	..	..	Average quality
Zinfandel	White table	..	..	..	..	Good quality
	Red table	..	..	..	..	Too much planted now

TABLE 8  
RECOMMENDATIONS FOR WINE TYPES AND REGIONAL ADAPTABILITY OF VARIETIES NOT FULLY TESTED\*

Variety	Type of wine	Region				Region V	Remarks
		I	II	III	IV		
Affenthaler.....	Red table .....	No	No (I)	No	No	No	Average quality
Aglianico.....	Red table .....	No	No (I)	No	No	No (I)	Deficient in color
Boal Madeira.....	White dessert.....	No	No	No	No	No (I)	Average quality
Catarrina.....	White table.....	?†	?†	?†	?†	No (I)	Average quality
Corbeau.....	Red table .....	No	No (I)	No	No	No (I)	Lates ripener; good quality
Erbaluce Caluso.....	White table.....	No	No	No	No	No (I)	Average quality
Eserio.....	Dry or sweet white table	..	..	No	No	No	Good production
Fogaruna.....	Red table .....	No	No	No	No	No (I)	Lacks color; ripens late
Furnant.....	Red table .....	No	No	No	No	No	Poor grapes
Grillo.....	White table .....	No	No	No	No	No	Average quality
Houigner.....	White dessert.....	No	No	No	No	No (I)	Good production
Malbec.....	White table .....	No	No	No	No	No (I)	Distinct flavor
Morlot.....	Red table .....	No	No (I)	No	No	No (I)	Average quality
Muscatel.....	White table .....	No	No	No	No	No (I)	High producer
Orieans.....	White table .....	No	No	No	No	No	Standard white
Robin noir.....	Pink table .....	No	No (I)	No	No	No	Fruity; lacks color
Waldehring.....	White table .....	No	No (I)	No	No	No	Pleasant; fruity wines

\* "No" recommendations followed by (I) mean that the variety should be planted in the region only under special circumstances, usually more completely explained in the text.

† Not tested; possibly useful for white table wine.

It must be remembered that these are relative values. As more information becomes available they will no doubt change, but the changes probably will be of small magnitude, arising primarily from the collection of grapes from better or poorer environmental conditions than those of the present samples. These figures will still serve as a guide for the selection and evaluation of varieties both for planting and for purchase. As they now stand, they clearly indicate one of the principal fallacies in the industry of today, namely, its failure to make sufficient price differential in the purchase of grapes of different varieties.

As stated above, the relative values for the varieties are for the region or regions to which they are best adapted. This is the only means by which the real value of the varieties for wine production can be approached. In general, the wines of a variety that possesses a high value in a cool region will lose in relative value more rapidly as it is grown in warmer and warmer areas than its productivity increases in these regions. This is well illustrated by Pinot noir, Petite Sirah, White Riesling, and others. Likewise, a variety adapted to region V, where its table wines possess a low value, will lose in productivity, as it is grown in cooler and cooler regions, more rapidly than the relative value of its wines increases.

The relative values of varieties for wine production are further influenced by their fruiting habit and productivity. The fruiting habit of a variety may necessitate special pruning systems, and its productivity is next in importance to the quality of the wines it produces. Therefore, the recommended system of pruning for each variety, and its relative productivity, were added to tables 5 and 6.

Table 7 summarizes the varietal recommendations concerning varieties fully tested for their regional adaptation and suitability for the recognized types of wine. Table 8 gives data for varieties not fully tested. Reference to the description of each variety which follows, together with the data in tables 9 to 23, will explain the selections more adequately.

### RECOMMENDED VARIETIES<sup>a</sup>

Only varieties which produce the best wine of their type, whether standard or quality red or white table or red or white dessert wines, are recommended. For varieties which cannot be unqualifiedly recommended see page 562.

#### VARIETIES FOR REGION I

Region I contains few fertile soils which are, or may well be, planted to vines. As a rule only hillside slopes of very moderate fertility are available for grapes (fig. 1). Heavy-bearing varieties should not be planted, since their production cannot compete with that of warmer and more fertile districts. In general, white varieties should be preferred to red.

(Text continued on page 588)

<sup>a</sup> The varieties collected and here listed have been in all cases, as nearly as can be determined, the same as those grown under these names in the variety collection of the University Farm at Davis. Probably not all have been correctly identified. Changes in the nomenclature of some varieties may be made, and the correct identification may be obtained by referring to later publications of this station or by writing to the Division of Viticulture, College of Agriculture, Davis. In the capitalization of variety names the authors have followed the style used in the ampelographies of Europe.

TABLE 9  
COMPOSITION OF MUSTS AND WINES OF WHITE VARIETIES PARTICULARLY RECOMMENDED FOR REGION I

Region	Number of samples	Average harvest date, and year	Must			Wine				
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol, per cent	Fixed acid, grams per 100 cc	Extract, grams per 100 cc	Tannin, grams per 100 cc	Color intensity*
Chardonnay										
III	1	Sept. 8, 1936	27.2	0.54	3.88	15.6	0.42	4.0	0.03	Very distinct; good, but alcoholic
IV	1	Aug. 31, 1936	23.5	.67	3.79	13.0	.39	-	-	Distinct; lacks acid; standard quality
I	2	Oct. 1, 1937	22.1	72	3.38	12.0	.52	2.0	.03	Light body; fruity; distinct; good quality
III	1	Sept. 11, 1937	24.6	63	3.69	12.8	.49	2.1	.03	Flat; tends to oxidize, but distinct
I	1	Sept. 14, 1938	19.8	.76	3.19	10.5	.68	2.8	.07	Tart, but palatable; distinct; picked too early
III	1	Sept. 25, 1938	25.2	.62	3.34	14.8	.59	2.8	.06	Soft, very rich, distinct; very good
IV	1	Sept. 8, 1938	25.0	.71	3.84	14.2	.48	2.9	.07	Distinct; rich; lacks acid
IV	1	Aug. 14, 1939	22.7	80	3.30	11.0	.62	2.7	.05	Fruity; delicate; average quality
III	1	Aug. 16, 1940	22.0	.66	3.23	12.8	.61	2.6	.04	Distinct; balanced; very good quality
IV	3	Aug. 23, 1940	22.9	.84	3.52	12.0	.68	2.7	.01	Surprisingly tart, fruity; good quality
III	2	Sept. 13, 1941	25.8	.60	3.22	13.8	.64	3.3	.07	Very rich, distinct; good quality; not dry
IV	3	Sept. 7, 1941	22.4	0.88	3.45	11.9	0.55	3.0	0.05	Very distinct, good flavor; average quality
Sauvignon blanc†										
II	1	... , 1935	...	...	...	13.8	0.41	2.5	0.04	Distinct flavor; low acid; tends to oxidize
III	1	Sept. 8, 1936	27.1	0.79	-	13.9	.70	4.3	.04	Aromatic flavor, grapes overripe
III	1	Sept. 11, 1937	24.5	0.63	3.61	13.0	0.60	2.1	0.03	Distinct flavor; fair acidity; good quality

		Oct. 8, 1938	25.6	0.44	3.28	15.4	0.42	2.1	0.05	26
III	1	Oct. 4, 1938	25.0	.43	3.69	14.9	.37	2.5	.05	18
IV	1	Sept. 24, 1939	25.2	.53	3.15	14.2	.58	2.6	.05	24
II	1	Sept. 9, 1939	24.4	.70	3.38	12.2	.47	1.9	.02	117
III	1	Sept. 7, 1939	23.3	.68	3.36	11.7	.52	2.4	.04	34
IV	2	Sept. 25, 1940	24.1	.74	3.30	13.8	.58	2.4	.02	23
I	1	Sept. 16, 1940	27.6	.65	3.42	13.9	.44	2.4	.01	18
II	2	Sept. 11, 1940	24.4	.67	3.42	13.8	.46	2.2	.01	18
III	2	Sept. 9, 1940	21.9	.68	3.46	12.1	.48	2.7	.01	39
IV	3	Sept. 28, 1941	27.0	.70	3.11	14.8	.61	3.1	.05	5
II	1	Sept. 13, 1941	25.0	.68	3.22	14.0	.68	2.8	.06	24
III	2	Oct. 2, 1941	23.6	.85	3.28	14.0	.69	3.1	.06	10
IV	7	Aug. 15, 1941	22.9	0.79	3.35	12.5	0.62	2.6	0.06	12
V	1									

White Riesling										
II	1	Sept. 20, 1935	22.0	0.56	..	11.7	0.34	2.1	0.06	..
IV	3	Sept. 23, 1936	23.4	.46	4.04	13.3	.34	2.9	.05	..
IV	2	Oct. 12, 1937	22.7	.71	3.41	12.4	.43	2.1	0.03	-
IV	4	Oct. 2, 1938	21.7	.53	3.73	11.9	.43	2.3	0.05	17
IV	2	Aug. 31, 1939	20.0	.76	3.15	12.2	.45	2.3	0.03	21
II	1	Sept. 11, 1940	22.8	.75	3.18	12.1	.69	2.2	.01	15
III	1	Sept. 4, 1940	24.2	.56	3.05	12.3	.55	2.4	.03	9
IV	7	Aug. 30, 1940	23.2	.83	3.21	12.9	.54	2.5	.02	19
II	1	Sept. 17, 1941	23.2	.63	3.11	13.4	.56	2.4	.09	8
III	1	Sept. 6, 1941	23.9	.72	3.06	13.3	.74	2.5	.07	11
IV	1	Sept. 5, 1941	21.1	0.84	3.17	12.2	0.67	2.5	0.07	10

\* Determined in a color comparator using an arbitrary color standard made from Eastman ABC dyes; the color intensity increases as the figures increase.  
 † Several natural sweet wines of distinct varietal flavor and good balance were also produced.

TABLE 10  
COMPOSITION OF MUSTS AND WINES OF RED VARIETIES PARTICULARLY RECOMMENDED FOR REGION I

Region	Number of samples	Average harvest date and year	Must			Wine			Tasting record
			Total acid, Ballard degrees	pH	Alcohol, per cent	Fixed acid, grams per 100 cc	Extract, tannin, grams per 100 cc	Color intensity*	
Cabernet Sauvignon									
I	2	Oct. 14, 1935	20.5	0.65	..	9.3	0.53	2.5	0.13
II	2	Oct. 22, 1935	23.3	0.84	..	12.0	.53	2.7	VR-15
III	2	Oct. 2, 1935	22.6	0.51	..	11.0	.55	2.7	VR-50
IV	2	Nov. 1, 1935	25.7	0.83	..	12.7	.35	3.5	3VR-35
I	3	Sept. 29, 1936	23.7	0.53	3.71	12.8	.67	2.5	1R-6
II	2	Sept. 25, 1936	25.3	0.53	0.45	14.5	.55	3.8	2R-28
III	2	Sept. 25, 1935	25.3	0.51	3.80	12.9	.50	3.0	4VR-20
IV	2	Sept. 25, 1935	24.9	0.51	3.95	12.3	.51	3.5	3R-27
I	4	Oct. 2, 1937	21.7	0.79	3.33	11.8	.59	2.6	1R-9
II	3	Oct. 2, 1937	22.9	0.55	3.14	12.8	.53	2.6	4VR-23
III	3	Sept. 18, 1937	22.4	0.53	3.39	11.8	.55	2.8	3VR-32
IV	1	Sept. 4, 1937	23.3	0.59	3.55	11.3	.39	2.1	4VR-27
V	1	Aug. 21, 1937	22.9	0.66	3.48	11.2	.49	2.2	JVR-18
I	3	Oct. 1, 1938	22.3	0.63	3.19	11.6	.73	2.8	4VR-34
II	3	Oct. 20, 1938	23.3	0.63	3.27	12.6	.29	1.9	3R-31
III	2	Sept. 23, 1938	23.5	0.53	3.33	13.1	.65	2.8	3R-15
IV	4	Oct. 14, 1938	22.5	0.55	3.69	11.7	.39	3.3	2VR-0
V	1	Aug. 31, 1938	22.0	0.46	3.55	10.9	.50	3.0	1-20
I	6	Oct. 12, 1939	23.5	0.74	3.13	12.6	.67	2.6	207
II	5	Sept. 28, 1939	24.6	0.64	3.14	13.3	.42	2.7	49
IV	5	Sept. 13, 1939	23.4	0.64	3.43	10.9	.42	2.7	236
V	5	Aug. 30, 1939	24.8	0.46	3.48	11.7	.50	3.1	265
I	4	Oct. 3, 1940	22.3	0.80	3.23	11.7	.63	2.7	297
II	4	Sept. 18, 1940	23.3	0.63	3.41	12.1	.62	2.9	341
III	2	Sept. 11, 1940	22.1	0.60	3.37	11.5	.51	2.6	147
IV	2	Sept. 18, 1940	22.4	0.73	3.51	10.7	.55	3.0	147
V	1	Aug. 15, 1940	23.1	0.51	3.25	13.1	.53	3.1	264
I	1	Oct. 10, 1941	23.2	1.00	3.09	12.7	.64	2.7	426
II	1	Oct. 22, 1941	23.9	0.65	3.21	12.7	.69	3.0	432
III	1	Sept. 20, 1941	23.5	0.55	3.27	12.4	.59	2.9	515
IV	2	Sept. 15, 1941	22.2	0.47	3.27	10.8	.52	2.9	243
V	1	Aug. 25, 1941	23.9	0.60	3.43	13.1	.59	4.2	290

		Gamay											
		Oct.	10, 1937	26.1	0.86	3.29	14.3	0.55	2.8	0.12	R-34		
III	1	Sept. 8, 1937	21.8	1.02	3.66	10.8	.48	3.1	.11			400	
III	1	Oct. 15, 1938	21.0	0.72	3.20	11.3	.51	2.5	.15	3VR-20		210	
III	1	Sept. 25, 1938	20.8	0.69	3.48	10.6	.69	3.1	.14	1R-23		200	
IV	2	Sept. 21, 1938	22.8	0.59	3.51	13.1	.57	3.4	.14	2R-13		133	
I	1	Sept. 29, 1939	21.5	0.64	3.28	11.8	.66	2.5	.12			290	
II	1	Sept. 23, 1939	23.6	0.80	3.00	12.6	.67	2.5	.10			222	
IV	3	Aug. 25, 1939	22.7	0.74	3.27	10.5	.45	2.6	.09			125	
I	1	Sept. 11, 1940	22.0	0.98	3.22	10.7	.60	2.9	.12			125	
II	1	Sept. 22, 1940	24.0	0.79	3.18	12.6	.68	2.7	.12			236	
IV	3	Aug. 13, 1940	22.3	0.83	3.35	11.5	.48	2.7	.05			86	
II	1	Sept. 28, 1941	24.5	0.88	3.01	12.7	.64	2.6	.16			241	
IV	4	Aug. 30, 1941	23.3	0.96	3.38	11.3	.61	3.2	.12			93	
V	1	Aug. 15, 1941	24.4	0.83	3.10	10.7	0.33	3.1	0.25			53	

Pinot noir													
		Sept. 10, 1936	23.4	0.77	3.30	11.9	0.45	2.9		5VR-13			
I	1	Sept. 24, 1938	22.2	.67	3.27	12.4	.73	2.9	0.18	R-33		153	
I	2	Sept. 10, 1938	24.7	.46	3.85	13.6	.35	3.3	.15	R-11		325	
V	1	Aug. 12, 1939	21.4	.86	3.28	8.7	.50	2.5	.07			102	
IV	1	Aug. 17, 1939	23.1	.39	3.48	11.2	.48	2.3	.08			151	
IV	2	Aug. 19, 1940	23.7	.75	3.44	11.6	.38	2.8	.11			109	
IV	2	Aug. 27, 1940	22.0	0.90	3.42	10.6	0.54	3.1	0.14			131	
												101	

\* Data in left column, by the Dujardin-Salleron vino-colorimeter; following Hilgard's procedure the observed figures have been divided into 4,000 so that the recorded figures will be proportional to intensity. Data in right column, by use of color standards and a color comparator.

TABLE II  
COMPOSITION OF MUSTS AND WINES OF WHITE VARIETIES PARTICULARLY RECOMMENDED FOR REGION II

Region	Number of samples	Average harvest date, and year	Must			Wine			
			Balling degrees	Total acid, grains per 100 cc	pH	Alcohol, per cent	Fixed acid, grains per 100 cc	Extract, grains per 100 cc	Tannin, grains per 100 cc
Folle blanche									
I	1	Oct. 21, 1935	17.9	0.66	...	8.7	0.56	2.2	0.04
II	2	Oct. 9, 1935	20.1	0.71	...	10.3	.60	2.1	0.04
III	1	Oct. 10, 1935	17.5	0.72	...	8.3	.66	1.9	0.04
I	3	Sept. 21, 1936	21.3	0.78	3.17	11.8	.59	2.5	0.04
II	1	Oct. 5, 1936	23.8	0.58	3.51	12.9	.56	2.5	0.03
I	1	Oct. 10, 1937	20.2	0.83	3.10	11.5	.72	1.8	0.03
II	1	Oct. 24, 1937	20.0	0.85	3.10	10.9	.60	2.0	0.04
III	1	Oct. 3, 1937	19.8	0.77	3.20	11.1	.67	2.2	0.03
I	1	Oct. 9, 1938	20.3	0.69	2.96	11.8	.71	2.4	0.06
II	1	Oct. 23, 1938	19.5	0.72	2.90	10.9	.80	2.3	0.06
III	1	Oct. 16, 1938	17.7	0.77	3.07	10.0	.73	2.4	0.05
I	2	Oct. 6, 1939	19.3	0.91	2.88	10.2	.67	2.0	0.04
II	2	Sept. 25, 1939	20.4	0.83	2.85	10.4	.73	2.2	0.04
III	1	Sept. 19, 1939	23.2	0.75	3.02	11.8	.60	2.1	0.03
IV	1	Oct. 13, 1939	23.5	0.68	3.56	20.3†	.35	2.4	0.02
V	1	Aug. 31, 1939	19.2	0.64	3.20	9.1	.47	2.0	0.02
I	4	Oct. 10, 1940	20.0	0.95	3.02	11.0	.75	2.2	0.02
II	1	Sept. 22, 1940	20.2	0.89	3.12	10.5	.75	2.2	0.02
III	1	Sept. 19, 1940	19.4	0.51	3.20	10.2	.60	2.0	0.02
IV	1	Sept. 25, 1940	21.1	0.78	3.57	10.9	.53	2.3	—
V	1	Aug. 29, 1940	18.6	0.73	3.22	10.1	.46	2.1	0.02
I	2	Oct. 8, 1941	20.7	1.03	3.01	11.6	.86	2.2	0.05
II	2	Sept. 26, 1941	19.7	0.87	2.95	11.1	.80	2.3	0.07
III	1	Sept. 20, 1941	22.4	0.71	3.14	12.3	.61	2.4	0.07
IV	1	Oct. 3, 1941	21.8	0.88	3.49	11.5	.42	2.5	0.04

\* For footnotes see page 525.

Pinot blanc												Semillon												
III	1	Sept. 25, 1935	19.7	0.80	..	9.5	0.60	2.3	0.03	..	..	Tart, thin; distinct, good quality												
IV	2	Sept. 20, 1935	22.6	.54	..	11.5	.48	2.4	0.04	..	..	Distinct, but flat, tends to spoil												
I	1	Sept. 10, 1936	22.8	.64	3.30	12.8	.45	2.1	0.05	..	..	Light, but with good flavor												
III	1	Sept. 22, 1936	22.4	.68	3.36	10.3	.56	..	..	..	..	Poor, incomplete fermentation												
IV	2	Sept. 4, 1936	22.9	.57	3.56	12.6	.35	2.2	0.03	..	..	Distinct aroma; very flat												
III	1	Sept. 18, 1937	23.1	.91	3.41	11.9	.46	2.3	0.03	..	..	Average character; excessive acid reduction												
IV	1	Aug. 26, 1937	22.0	.67	3.63	12.0	.45	2.0	0.04	..	..	Oxidized; tends to spoil												
IV	3	Sept. 23, 1938	22.2	.58	3.69	12.3	..	3.0	0.07	19	19	Rich; flat; distinct flavor												
V	1	Sept. 10, 1938	26.2	.36	3.88	15.0	.50	3.4	0.07	13	13	Rich; high final acid because of bacteria												
I	1	Sept. 9, 1939	23.6	.77	3.14	12.1	.57	2.0	0.04	23	23	Smooth; balanced; good distinct quality												
III	1	Oct. 1, 1939	23.6	.57	3.33	13.6	.39	2.4	0.04	21	21	Rich; flat; distinct flavor												
IV	2	Aug. 17, 1939	21.9	.62	3.38	11.2	.57	2.4	0.03	23	23	Fruity; good character, note early harvest												
V	1	Aug. 17, 1939	25.7	.35	3.85	13.1	.50	2.6	0.03	12	12	Very distinct flavor; tends to oxidize												
III	1	Sept. 10, 1940	22.2	.63	3.52	12.0	.42	2.1	0.02	14	14	Rich; flat; lacks delicacy												
IV	3	Aug. 20, 1940	20.6	.71	3.46	11.2	.41	2.1	0.02	17	17	Distinct, good quality, despite acid reduction												
V	1	July 28, 1940	21.9	.62	3.52	13.3	.50	2.5	0.02	11	11	Distinct; rich, tends to oxidize												
IV	3	Sept. 7, 1941	23.0	.79	3.34	12.6	.67	2.6	0.06	18	18	Distinct flavor; good acidity; quality												
V	1	Aug. 15, 1941	23.8	0.69	3.68	12.4	0.47	2.5	0.06	15	15	Rich flavor, fairly well balanced												

(Continued on following page)

TABLE II—(Continued)

Region	Number of samples	Average harvest date, and year	Must			Wine			
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol, per cent	Fixed acid, grams per 100 cc	Extract, grams per 100 cc	Tannin, grains per 100 cc
Semillon—(Continued)									
I	1	Oct. 5, 1937	21.0	0.68	3.10	11.9	0.55	2.0	0.03
II	4	Oct. 15, 1937	23.3	.49	3.45	13.1	.39	3.0	.03
III	7	Sept. 22, 1937	22.9	.55	3.46	12.3	.41	2.7	.03
IV	6	Oct. 16, 1937	22.4	.52	3.45	12.3	.30	4.3	.03
V	1	Aug. 27, 1937	23.2	.68	3.89	11.7	.50	1.8	.03
I	3	Oct. 13, 1938	22.4	.57	3.23	13.1	.68	2.5	.05
II	2	Oct. 9, 1938	21.7	.48	3.45	12.9	.55	2.3	.04
III	1	Oct. 16, 1938	23.4	.48	3.40	13.6	.53	2.3	.04
IV	3	Oct. 19, 1938	19.0	.51	3.60	11.0	.45	2.1	.05
V	2	Aug. 23, 1938	21.4	.45	3.41	12.5	.42	2.7	.06
I	5	Oct. 1, 1939	22.1	.63	3.17	11.9	.53	1.9	.03
II	3	Sept. 25, 1939	24.9	.67	3.33	13.7	.53	2.1	.03
III	3	Sept. 25, 1939	23.1	.63	3.35	12.3	.49	2.1	.03
IV	5	Sept. 25, 1939	24.2	.51	3.56	12.7	.43	3.4	.04
V	2	Aug. 24, 1939	21.4	.41	3.59	11.5	.38	2.0	.03
I	4	Oct. 6, 1940	21.8	.73	3.24	12.5	.57	2.2	.01
II	2	Sept. 11, 1940	23.5	.51	3.58	12.1	.47	3.7	.01
III	8	Sept. 16, 1940	24.1	.63	3.72	13.3	.37	4.0	.02
IV	2	Aug. 23, 1940	22.5	.45	3.43	12.1	.45	3.9	.03
V	2	Oct. 8, 1941	24.6	.84	3.20	13.4	.72	3.1	.04
II	1	Sept. 17, 1941	22.8	.60	3.24	12.8	.56	2.3	.06
III	1	Sept. 20, 1941	25.6	.47	3.41	14.4	.52	2.5	.03
IV	3	Oct. 3, 1941	21.2	.62	3.49	11.5	0.52	2.5	.08
V	1	Aug. 25, 1941	19.6	0.50	3.25	11.0	—	2.2	0.07

Sylvaner									
II	2	Oct. 10, 1936	23.3	0.56	.	12.1	0.40	2.2	0.04
IV	3	Sept. 20, 1936	22.1	.49	.	10.9	.41	2.4	0.03
I	1	Sept. 26, 1936	23.7	.58	3.25	13.1	.42	2.3	0.04
II	1	Sept. 27, 1936	22.9	.55	3.61	13.3	.43	2.1	0.03
IV	1	Sept. 13, 1936	25.5	.30	4.00	13.9	.38	2.1	0.04
I	2	Oct. 16, 1937	22.6	.61	3.39	12.2	.37	1.9	.03
II	1	Sept. 22, 1937	24.7	.69	3.46	13.2	.50	2.1	0.03
III	1	Sept. 11, 1937	22.6	.63	3.51	12.3	.44	2.0	0.03
IV	1	Sept. 20, 1937	23.7	.51	3.74	12.2	.38	2.2	0.03
I	1	Oct. 21, 1938	24.5	.46	3.45	13.6	.49	2.6	0.05
II	2	Oct. 6, 1938	22.9	.43	3.29	13.1	.45	2.7	0.04
IV	3	Sept. 19, 1938	22.2	.57	3.66	13.4	.51	3.0	0.06
I	4	Oct. 3, 1939	23.4	.65	3.13	12.7	.49	2.1	0.03
IV	4	Aug. 29, 1939	23.7	.73	3.40	11.4	.58	2.5	0.03
I	3	Sept. 28, 1940	22.8	.58	3.46	12.4	.41	2.1	0.03
II	3	Sept. 22, 1940	23.5	.68	3.34	13.3	.53	2.8	0.02
IV	5	Aug. 20, 1940	20.7	.70	3.40	12.1	.54	2.3	0.02
I	1	Oct. 10, 1941	23.3	.90	3.10	13.0	.76	2.5	0.03
II	2	Sept. 24, 1941	24.6	.65	3.40	13.5	.54	2.6	0.05
IV	3	Sept. 11, 1941	22.9	0.75	3.44	12.5	0.65	2.8	0.05

\* Determined in a color comparator using an arbitrary color standard made from Eastman ABC dye; the color intensity increases as the figures increase.

† Grapes brandy added to increase alcohol content.

Distinct aroma, flavor, full body, average quality  
Distinct aroma, flavor; smooth; very good

Flat; ordinary because of poor fermentation.  
Pleasing, distinct aroma, soft; balanced; good  
Distinct, pleasant aroma; smooth; somewhat flat

Light; delicate; not distinct; good  
Medium; distinct; balanced; average quality  
Distinct aroma, flavor; balanced; very good  
Pleasing, typical character; flat but good

Very distinct aroma, flavor; balanced; good  
Distinct aroma; excellent flavor, good quality  
Distinct aroma; very fruity, good  
Very distinct aroma, fruity, good character  
Very distinct aroma, fruity; soft; good quality  
Distinct aroma, fruity, soft, good character  
Distinct aroma, balanced; good quality  
Pleasing, distinct aroma; balanced; good

Tart; light color and body; not distinctive  
Rich; one sample especially distinct; good quality  
Fruity; distinct; good, note early harvest.

TABLE 12  
COMPOSITION OF MUSTS AND WINES OF RED VARIETIES PARTICULARLY RECOMMENDED FOR REGION II

Region	Number of samples	Average harvest date and year	Must			Wine			Color intensity*	Tasting record
			Balling degrees	Total acid, grains per 100 cc	pH	Alcohol, per cent	Fixed acids, grains per 100 cc	Tannin, grains per 100 cc		
Petite Sirah										
I	3	Oct. 24, 1935	22.1	0.79	.61	2.7	0.31	3VR-23	-	Varietal aroma; balanced, good quality; slow-maturing
II	5	Oct. 11, 1935	20.7	.56	10.9	2.6	19	3VR-40	-	Characteristic aroma, flat; slow-naturig
III	4	Oct. 4, 1935	21.8	.463	10.7	2.9	.18	2VR-36	-	Good color; raisin flavor in some samples; average
IV	6	Oct. 20, 1935	20.1	.81 <sup>a</sup>	12.9	4.5	3.1	3R-37	-	Tends to oxidize, ordinary quality
V	3	Aug. 28, 1935	21.8	.73	10.1	5.1	2.7	21	3VR-38	Distinct flavor; sound, picked too early
I	2	Sept. 30, 1936	23.3	.57	3.64	13.8	63	3.1	27	2VR-76
II	6	Oct. 1, 1936	24.5	.52	4.01	15.0	54	3.3	25	3VR-51
III	12	Sept. 25, 1936	26.6	.53	4.06	14.9	.59	3.7	33	2VR-47
IV	4	Sept. 26, 1936	28.1	.57	4.05	14.2	49	4.1	34	2R-50
V	4	Aug. 23, 1936	23.6	.61	3.99	11.9	45	3.0	21	3VR-25
I	2	Oct. 11, 1937	22.4	.67	3.43	12.5	.54	2.7	.30	3R-40
II	7	Oct. 9, 1937	22.0	.66	3.40	12.4	.47	2.5	.20	VR-39
III	11	Sept. 20, 1937	24.7	.67	3.61	13.1	.55	2.7	.20	VR-27
IV	12	Oct. 5, 1937	24.1	.69	3.63	12.7	.41	2.8	.20	3R-23
V	2	Sept. 16, 1937	23.1	.52	3.64	12.6	.52	3.0	.23	3VR-25
I	1	Oct. 16, 1938	21.0	.71	3.46	12.7	.67	3.3	33	4VR-70
II	2	Oct. 19, 1938	21.3	.67	3.15	12.8	.58	2.9	24	Rough; slow-naturig; good flavor, average quality
III	7	Oct. 5, 1938	19.1	.58	3.13	11.5	.69	2.6	20	Varietal aroma, average quality
IV	10	Sept. 28, 1938	22.7	.53	3.53	12.7	.52	2.9	18	Early-picked samples fruity, but lack character, two pink wines were of better balance
V	1	Aug. 31, 1938	21.0	.65	3.50	11.3	.47	2.3	0.23	High tannin; flat; rough; poor

I	3	Sept. 30, 1939	21.1	0.74	3.06	11.7	0.69	2.3	0.17	568
II	9	Sept. 26, 1939	23.1	0.64	3.20	12.3	0.62	2.6	0.14	566
III	2	Sept. 15, 1939	25.6	0.78	3.25	12.3	0.55	3.6	0.13	337
IV	3	Sept. 12, 1939	21.7	0.67	3.29	11.1	0.41	2.8	0.13	212
V	1	Aug. 30, 1939	23.0	0.50	3.62	11.1	0.60	2.6	0.15	400
I	3	Oct. 1, 1940	21.7	0.95	3.15	12.1	0.68	2.5	0.18	339
II	3	Sept. 16, 1940	21.4	0.81	3.27	12.7	0.66	3.1	0.21	380
III	3	Sept. 9, 1940	20.4	0.69	3.32	10.2	0.43	2.4	0.14	222
IV	4	Sept. 23, 1940	23.1	0.64	3.55	10.8	0.48	2.8	0.14	372
V	1	Aug. 29, 1940	22.4	0.66	3.53	19.1†	0.36	9.5	0.14	201
II	3	Sept. 30, 1941	23.0	0.68	3.24	12.3	0.59	2.8	0.23	450
III	1	Sept. 6, 1941	18.8	1.08	2.90	6.5	0.56	2.3	0.23	227
IV	2	Sept. 23, 1941	26.5	0.55	3.52	12.8	0.53	3.1	0.26	269
V	1	Aug. 15, 1941	22.1	0.66	3.29	10.3	0.50	2.8	0.16	222

Refosco											
II	1	Oct. 1, 1935	24 6	0 65	-	12 9	0 49	2 2	0 16	5YR-25 3VR-33	
V	1	Sept. 6, 1935	22 4	70	-	10 9	60	2 5	27		
I	1	Oct. 7, 1936	20 6	.49	3 55	10 9	-	3 0	R-15	132	
IV	1	Sept. 25, 1936	26 5	70	3 96	13 8	50	3 9	3VR-33	620	
I	1	Oct. 21, 1937	20 2	80	3 29	10 7	56	2 3	5YR-33	353	
IV	1	Oct. 7, 1937	23 6	60	3 64	13 9	45	2 8	3YR-36	388	
I	1	Oct. 21, 1938	24 1	57	3 55	14 2	52	3 2	3YR-6	280	
IV	4	Sept. 25, 1938	20 9	63	3 51	10 7	62	3 1	VR-9	117	
IV	5	Oct. 15, 1939	22 8	58	3 49	10 8	55	2 5	15	199	
IV	3	Sept. 27, 1940	21 5	.66	3 51	10 9	49	2 7	18	-	265
IV	2	Sept. 27, 1941	20 0	0 61	3 31	11 0	0 67	2 5	0 26		427

**Data in left column.** By the Djadid-Salleon wine-colorimeter, following Hillebrand's procedure, the observed figures have been divided into 4,000 so that the recorded figures will be proportional to the amount of color in milligrams per liter. The use of color standards and a colorimetric comparator will be described in another paper.

TABLE 13  
COMPOSITION OF MUSTS AND WINES OF WHITE VARIETIES PARTICULARLY RECOMMENDED FOR REGION III

Region	Number of samples	Average harvest date, and year	Must			Wine				
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol, per cent	Fixed acid, grains per 100 cc	Extract, grains per 100 cc	Tannin, grains per 100 cc	Color intensity,*
French Colombard										
IV	1	Oct. 3, 1935	23.6	0.70	..	11.3	0.64	2.3	0.03	Distinct aroma, flavor; smooth; very good
IV	1	Oct. 2, 1937	21.5	0.75	3.52	11.5	0.68	..	0.02	Distinct aroma; pleasant, fruity; balanced
I	1	Sept. 27, 1939	19.9	0.86	3.00	10.4	0.68	2.0	0.04	Tart; fruity; flavorful; good
IV	2	Aug. 22, 1939	22.2	0.91	3.30	10.2	0.62	2.5	0.03	Medium distinct aroma; fruity flavor; fresh
I	1	Sept. 25, 1940	20.0	0.85	3.15	11.8	0.65	2.1	0.02	Distinct aroma; pleasant; gray; good quality
II	1	Oct. 11, 1940	20.6	0.98	3.10	10.8	0.44	2.4	0.02	Distinct aroma; fruity; pleasant
III	1	Sept. 19, 1940	23.2	0.85	3.20	12.6	0.63	2.3	0.02	Distinct aroma; good flavor; not balanced
IV	3	Aug. 28, 1940	19.5	1.10	3.44	11.0	0.56	2.6	0.02	Fruity; very pleasant, balanced
II	1	Sept. 17, 1941	23.9	0.89	2.99	13.2	0.76	2.5	0.04	Very distinct; fruity; good quality
III	1	Sept. 20, 1941	22.0	0.89	2.99	12.0	0.87	2.8	0.07	Moderate flavor; tart; well balanced
IV	2	Sept. 16, 1941	21.2	0.99	3.33	11.0	1.01	3.1	0.00	Medium distinct; fruity; tart; balanced
Muscat Canelli										
V	2	Aug. 12, 1935	25.7	0.85	....	13.7	0.52	5.5	0.09	Distinct, perfumed aroma; smooth; very good
V	3	Aug. 13, 1936	25.1	.54	3.92	16.8†	.32	9.7	.05	Distinct muscat; rich, luscious flavor; good
V	2	Sept. 3, 1937	23.1	.58	3.65	12.1	.43	2.7	.05	Distinct muscat; fruity; full flavor; good
IV	2	Sept. 24, 1938	26.5	.46	3.41	19.1†	0.42	11.5	.07	Distinct muscat; fruity, balanced
V	1	Aug. 14, 1938	24.1	0.45	3.50	15.6†	..	15.8	0.07	Very distinct, fruity muscat; gold color

II	1	Sept. 21, 1939	26.5	0.53	3.22	19.8†	0.31	14.1	0.03	39
III	1	Sept. 19, 1939	25.3	.62	3.25	18.5†	.41	13.4	.06	37
IV	3	Sept. 22, 1939	27.4	.50	3.53	17.8†	.38	11.7	.03	53
V	1	Aug. 30, 1939	27.8	.41	3.70	19.9†	.34	13.9	.03	17
III	1	Sept. 19, 1940	18.4	.67	3.48	9.0	.55	4.7	.02	16
IV	3	Sept. 19, 1940	23.2	.73	3.42	12.5	.55	2.5	.03	9
V	1	Aug. 15, 1940	26.5	.33	3.55	18.4†	.31	15.9	.06	15
III	1	Sept. 20, 1941	23.6	.70	3.15	13.7	.62	2.8	.03	21
IV	2	Oct. 8, 1941	28.2	.70	3.55	19.4†	.40	14.8	.03	14
V	2	Aug. 18, 1941	25.7	0.52	3.57	17.9†	0.33	14.4	0.05	48

\* Determined in a color comparator using an arbitrary color standard made from Eastman ABC dyes; the color intensity increases as the figures increase.

† Fermentation arrested by the addition of grape brandy.

TABLE 14  
COMPOSITION OF MUSTS AND WINES OF RED VARIETIES PARTICULARLY RECOMMENDED FOR REGION III

Region	Number of samples	Average harvest date, and year	Must			Wine			Tasting record
			Balling degrees	pH	Alcohol, per cent	Fried, acid, grams per 100 cc	Extract, Tannin, grams per 100 cc	Color intensity*	
Barbera									
III	1	Oct. 2, 1936	22.0	0.91	..	10.5	0.78	0.10	3YR-33
IV	1	Sept. 23, 1936	21.3	0.89	..	10.0	0.72	2.6	3YR-20
V	1	Aug. 23, 1936	20.7	1.00	..	9.5	0.73	2.8	3YR-13
II	1	Sept. 30, 1936	24.7	0.65	3.46	14.2	0.63	2.9	22
III	1	Sept. 23, 1936	28.1	0.63	3.60	14.7	0.60	3.1	20
IV	1	Sept. 13, 1936	24.0	0.66	3.19	12.6	0.48	3.1	11
V	2	Aug. 21, 1936	22.0	0.81	3.23	11.5	0.53	3.1	0.9
II	1	Oct. 13, 1937	22.0	0.68	3.36	12.1	0.63	2.3	16
III	2	Sept. 21, 1937	25.6	1.07	3.33	13.5	0.75	3.0	15
IV	1	Sept. 26, 1937	24.2	0.73	3.48	13.9	0.60	3.0	12
II	1	Oct. 15, 1938	22.6	0.70	3.11	12.7	0.75	2.9	19
III	3	Sept. 29, 1938	20.6	1.05	2.98	10.3	1.01	3.1	13
IV	3	Oct. 2, 1938	23.2	0.88	3.37	12.8	0.67	3.2	15
II	1	Oct. 4, 1939	24.8	0.57	3.32	13.9	0.59	.2.9	.17
IV	4	Sept. 2, 1939	23.6	1.01	3.17	11.5	0.77	2.7	0.9
V	1	Aug. 17, 1939	23.6	0.67	3.26	10.9	0.70	2.7	0.9
III	1	Sept. 4, 1940	24.7	1.03	3.10	11.3	0.95	3.2	16
IV	3	Sept. 14, 1940	23.9	1.02	3.32	11.9	0.71	2.9	.10
IV	3	Sept. 18, 1941	22.5	1.21	3.01	11.6	0.64	2.8	0.10

\* For footnotes to table see page 532.

Cognacname											
I	2	Oct. 20, 1935	20.5	0.71	-	10.1	0.56	2.3	0.09	4VR-16	
II	5	Oct. 3, 1935	20.5	0.69	10.8	50	2.7	11	3R-9		
III	3	Sept. 30, 1935	22.0	0.72	-	10.9	60	2.5	11	3R-18	
IV	5	Oct. 7, 1935	22.3	0.66	-	11.1	51	2.7	.08	VR-12	
V	3	Aug. 28, 1935	22.1	0.65	10.6	53	2.8	13	2YR-25		
I	3	Oct. 6, 1936	22.6	0.49	4.07	11.7	64	2.9	15	3R-21	348
II	4	Sept. 5, 1936	21.8	0.61	3.86	12.0	47	2.8	11	3R-10	226
III	5	Sept. 18, 1936	24.7	0.41	3.73	13.2	49	4.8	13	4VR-27	498
IV	4	Sept. 11, 1936	23.5	0.48	4.07	12.5	.57	3.1	13	VR-13	231
V	6	Sept. 1, 1936	22.3	0.54	3.74	12.1	43	5.6	12	VR-13	179
I	3	Oct. 16, 1937	19.9	0.84	3.19	10.7	.54	2.3	11	3R-14	255
II	4	Oct. 6, 1937	20.4	0.78	3.37	10.9	40	2.3	.06	VR-10	153
III	5	Oct. 5, 1937	23.3	0.69	3.49	12.0	56	2.5	12	4VR-21	298
IV	2	Oct. 1, 1937	22.7	0.55	3.63	12.1	43	2.4	.08	4VR-11	103
V	1	Oct. 12, 1937	21.8	0.62	3.67	11.9	43	2.6	.09	R-11	125
I	1	Oct. 21, 1938	22.2	0.79	3.36	13.1	.55	3.2	20	4VR-31	200
II	1	Oct. 28, 1938	24.0	0.87	3.09	13.0	66	2.7	18	R-22	270
III	3	Sept. 28, 1938	20.3	0.68	3.37	11.3	69	2.8	11	VR-19	180
IV	1	Oct. 12, 1938	21.4	0.69	3.57	11.9	37	2.3	11	3YR-9	80
I	2	Sept. 28, 1939	21.3	0.79	3.15	11.3	61	2.1	14		203
II	4	Sept. 27, 1939	21.7	0.65	3.19	11.6	63	2.3	11	Usually fruity, balanced, average quality	212
III	2	Sept. 22, 1939	23.6	0.80	3.17	12.7	76	2.9	10	Lacks character; average quality	226
IV	1	Oct. 6, 1939	25.3	0.44	3.72	17.0†	37	9.3	.05	Clean, deficient in color	115
V	3	Aug. 31, 1939	22.7	0.45	3.35	16.1†	47	7.7	.08	Well-balanced red dessert wine. An early harvested lot made standard table wine	131
III	3	Sept. 22, 1940	22.7	0.81	3.27	12.5	63	2.8	.13	Simple; fairly well balanced; average quality	289
IV	2	Sept. 13, 1940	23.6	0.68	3.53	20.1†	37	12.4	.06	Ordinary dessert wine; table wine flat	211
V	1	Aug. 29, 1940	23.2	0.60	3.58	16.9†	37	11.7	.11	Well-balanced red dessert wine	210
I	1	Sept. 28, 1941	21.9	0.99	3.07	11.1	.74	2.8	.15	Fruity, tart; only common flavor	400
III	2	Sept. 17, 1941	20.4	1.11	3.09	10.4	.70	2.6	.09	Tart, fruity; thin, little character	110
IV	1	Oct. 23, 1941	24.8	0.65	3.48	13.7	0.53	2.9	0.60	Alcoholic; common flavor; average quality	140

(Continued on following page)

TABLE 14—(Continued)

Region	Number of samples	Average harvest date and year	Must			Wine				Tasting record
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol per cent	Fixed acid, grams per 100 cc	Extract, Tannin, grams per 100 cc	Color intensity*	
Trouseau†										
IV	3	Oct. 3, 1935	25.1	0.56	..	13.3	0.43	3.4	0.07	VRY-6 3Ry-5
V	1	Sept. 4, 1935	20.7	.63	..	11.3	43	2.7	.08	Mild spicy flavor; flat; heavy, poor quality Light; clean; fairly fresh; tends to oxidize
I	1	Oct. 7, 1936	27.2	.45	4.38	16.5	.36	13.9	.09	Fruity, pleasant flavor; smooth; average quality
IV	3	Sept. 22, 1936	28.0	.40	4.40	17.8	.32	13.0	.05	Spry and lucious, smooth; raisin taste
V	3	Aug. 12, 1936	24.6	.50	4.37	19.1	.33	11.7	.05	Fruty and pleasant; smooth; tawny
IV	3	Sept. 25, 1937	25.3	.63	3.83	17.4	.32	9.9	.09	Grapy; smooth; slight caramel, tawny, very good
V	3	Sept. 3, 1937	25.5	.54	3.90	16.3	.33	7.7	.07	Fruty, excellent flavor; soft; tawny, very good
IV	3	Oct. 6, 1938	26.5	.49	4.35	19.3	.31	12.4	.06	Good flavor; smooth; well balanced; average
V	3	Sept. 5, 1938	24.9	.41	3.68	19.1	.39	13.7	.07	Fruity, lucious; balanced; very good quality
I	1	Sept. 27, 1939	25.9	.60	3.25	17.4	.49	10.0	.07	Distinct; fruity; smooth, balanced
IV	2	Oct. 3, 1939	29.8	.47	3.91	20.9	.44	10.8	.05	Raisin taste; soft; average quality
V	2	Aug. 30, 1939	27.0	.48	3.62	18.3	.42	10.7	.05	Fruity; pleasant; smooth; balanced
IV	5	Oct. 12, 1940	24.6	.64	3.77	18.3	.33	11.2	.08	Fruity; soft; balanced, tawny; good
V	2	Aug. 10, 1940	27.6	.41	3.67	17.1	.34	13.8	.11	Slight raisin taste, balanced; smooth, pleasant
IV	1	Oct. 24, 1941	27.1	.67	3.84	19.6	.41	12.8	.08	Slight raisin taste, balanced; smooth
V	2	Aug. 26, 1941	25.9	0.56	3.62	21.6	0.37	12.4	0.10	Fruity; soft, well balanced; good quality

\* Data in left column, by Dujardin-Salleron vino-colorimeter; following Hilgard's procedure, the observed figures have been divided into 4,000 so that the recorded figures will be proportional to intensity. Data in right column, by use of color standards and a color comparator.

† Fermentation arrested by the addition of grape brandy.

‡ Fermentation of all the samples of Trouseau from 1936 on was arrested by the addition of grape brandy.

*White Varieties.*—Recommended white varieties for high-quality dry table wines are White Riesling, Chardonnay, and Sauvignon blanc, the first two being the most desirable. Red Traminer is useful but should be planted only in the very coolest locations for producing an aromatic wine. Sylvaner is not recommended for this region, since it is so susceptible to mildew in foggy locations. Varieties such as Burger and Folle blanche should be avoided, since they will not ripen. Table 9 gives analyses of the recommended varieties.

*Red Varieties.*—Recommended red varieties for high-quality table wines are Cabernet Sauvignon and Pinot noir; and for standard or blending table wines are Gamay and Grenache.

Table 10 gives analyses of musts and wines of these varieties collected from the various regions, except for the Grenache (table 17).

#### VARIETIES FOR REGION II

In region II may be found both valley-floor vineyards and hillside vineyards. The former should produce most of the standard red and white table wines of California; the less productive hillside vineyards, though unable to compete for standard wines, can nevertheless produce fine wines.

*White Varieties.*—Recommended white varieties for high-quality dry table wines are Pinot blanc, White Riesling, and Sauvignon blanc (usually for natural sweet wine); and for standard, special, or blending dry table wines are Semillon (for dry or natural sweet wine), Sylvaner, and Folle blanche. Red Veltliner is useful but less desirable.

Table 11 gives analyses of musts and wines of the recommended varieties collected from this and the other regions except for the White Riesling and Sauvignon blanc (see table 9).

*Red Varieties.*—The recommended red variety for high-quality table wines is Cabernet Sauvignon.

Recommended red varieties for standard, special, or blending wines are Grenache, Petite Sirah, and Refosco. Also possible but less desirable are Mondeuse and Tannat.

Table 12 gives the analyses of musts and wines of the recommended varieties from various regions except for Cabernet Sauvignon (table 10) and Grenache (table 17).

#### VARIETIES FOR REGION III

The warm conditions of region III favor the production of grapes of greater sugar content without too much sunburning and too little acidity, which may occur in still warmer regions. Most of the vineyards are on fairly flat land, but some of the soils are rocky and of low productivity. The better-quality natural sweet wines come from the latter soils. It is a mistake to hope for *dry* wines of the finest quality in this region, even on the less fertile soils, since better-balanced wines of this quality can be had in regions I and II. However, excellent natural sweet wines should be produced. Good standard whites and reds also can be produced on the more fertile soils. Trouseau, though not particularly recommended on account of the cost of production, will produce very good red dessert wines in this region.

*White Varieties.*—Recommended white varieties for natural sweet wines are Semillon, Sauvignon blanc, and Muscat Canelli (by itself). Not ordinarily recommended are Chenin blanc and Muscadelle (by itself).

(Text continued on page 540)

TABLE 15  
COMPOSITION OF MUSTS AND WINES OF WHITE VARIETIES PARTICULARLY RECOMMENDED FOR REGION IV

Region	Number of samples	Average harvest date and year	Must			Wine			
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol, per cent	Fixed acid, grams per 100 cc	Extract, grams per 100 cc	Tannin, grams per 100 cc
Malvasia bianca									
IV	1	Sept. 30, 1936	30.0	0.30	4.06	20.9†	0.27	13.2	0.03
V	2	Aug. 13, 1936	23.8	4.7	3.82	13.6	32	2.2	0.02
III	1	Oct. 3, 1937	23.1	.66	3.31	12.4	.50	2.2	0.02
IV	2	Oct. 15, 1937	21.0	.72	3.36	12.6	.51	2.4	0.01
V	1	Aug. 27, 1937	24.0	5.6	3.96	11.2	47	2.2	0.03
III	1	Oct. 16, 1938	23.6	69	3.47	19.5†	.44	11.8	0.04
IV	2	Oct. 3, 1938	27.5	42	3.83	19.7†	.38	13.6	0.05
V	1	Aug. 31, 1938	25.0	36	3.61	18.8†	.31	13.7	0.05
III	1	Oct. 1, 1939	22.7	61	3.20	12.5	.55	2.1	0.02
IV	1	Sept. 25, 1939	28.2	39	3.79	18.6†	.32	14.2	0.03
V	1	Aug. 30, 1939	23.2	35	3.64	21.1†	.33	6.9	0.02
III	2	Sept. 11, 1940	22.5	69	3.33	12.1	.62	2.2	0.01
IV	1	Sept. 10, 1940	24.7	61	3.48	10.0	.45	8.5	0.01
IV	2	Oct. 11, 1941	26.4	60	3.50	21.0†	.39	12.6	0.06
V	1	Aug. 21, 1941	23.4	0.56	3.43	18.0†	0.51	11.9	0.05
Orange Muscat†									
IV	1	Sept. 23, 1937	26.0	0.64	3.56	19.8	0.38	11.0	0.09
IV	1	Oct. 3, 1938	23.1	43	3.69	19.3	28	12.5	0.04
IV	2	Sept. 19, 1939	25.5	49	3.72	19.3	.34	12.9	0.03
IV	2	Oct. 13, 1940	26.7	47	3.93	20.0	.33	14.6	0.04
V	1	Aug. 16, 1940	26.0	39	3.73	19.5	.33	14.3	0.06
IV	2	Oct. 10, 1941	28.7	58	3.88	18.3	.39	14.1	0.05
V	1	Aug. 21, 1941	24.4	0.57	3.48	18.9	0.39	13.5	0.06

Luscious, fruity muscat flavor, good quality  
 Flut; rather perfumed; dry, ordinary. Dessert wines of  
 duplicate lots were of distinct aroma, and good quality  
 Distinct, slightly harsh, flat; becomes amber  
 Distinct, dry muscat; typically harsh; flat. Dessert  
 wines of duplicate lots had strong muscat aroma,  
 were soft, and of good quality  
 Very poor, dry muscat; distinctly varietal  
 Fruity; very distinct muscat, good quality  
 Luscious, fruity, very distinct muscat, good quality  
 Very distinct varietal flavor; balanced; fruity  
 Very distinct, dry muscat; rather smooth  
 Fruity, distinct muscat, soft, excellent quality  
 Very fruity, distinct, aromatic; too dry, very good  
 Dry; average quality, fruity, lacks varietal flavor  
 Natural sweet; deficient in varietal aroma  
 Medium distinct, rich, flat; average quality  
 Lacks flavor, thin, ordinary

Average muscat; tends to sherry.  
 Fruity; distinct muscat; above average quality

Palomino									
I	2	Oct. 17, 1935	19.5	0.30	9.9	0.37	1.9	0.04	-
II	6	Oct. 14, 1935	21.3	.35	11.1	.35	2.1	.03	-
III	2	Oct. 6, 1935	21.9	.35	11.3	.35	2.3	.03	-
IV	5	Sept. 26, 1935	21.5	.32	10.6	.31	2.3	.03	-
V	3	Aug. 24, 1935	22.8	.49	11.0	.35	2.5	.08	-
I	1	Oct. 7, 1936	23.3	.21	3.37	13.2	4.6	2.3	0.3
II	8	Sept. 21, 1936	23.1	.29	3.85	12.5	3.4	2.5	0.02
III	2	Sept. 22, 1936	25.9	.42	3.83	13.1	4.3	2.7	0.3
IV	8	Sept. 22, 1936	23.9	.28	3.97	12.3	2.9	2.4	0.03
V	5	Aug. 1, 1936	20.2	.40	3.88	10.6	3.1	2.1	0.03
II	5	Oct. 9, 1937	21.7	.49	3.48	11.9	3.7	1.9	0.03
III	3	Oct. 4, 1937	22.2	.47	3.57	11.9	4.0	2.1	0.03
IV	3	Sept. 22, 1937	22.8	.39	3.68	12.4	3.4	2.0	0.04
V	1	Oct. 12, 1937	23.7	.31	3.86	13.7	2.2	2.1	0.04
I	2	Oct. 18, 1938	20.9	.39	3.51	16.0†	3.8	2.5	0.4
III	1	Oct. 4, 1938	21.4	.23	3.50	11.8	.-	1.9	0.05
IV	3	Oct. 13, 1938	22.8	.48	3.77	13.2	.41	2.6	0.06
I	1	Oct. 3, 1939	24.1	.44	3.39	13.3	4.0	2.4	.06
II	2	Sept. 24, 1939	22.1	.51	3.32	12.3	4.6	2.0	0.03
III	2	Sept. 20, 1939	23.1	.57	3.45	13.2	6.2	2.4	0.05
IV	2	Sept. 20, 1939	22.7	.41	3.55	11.1	3.5	2.0	0.05
IV	2	Oct. 21, 1939	25.2	.37	3.83	21.5†	2.7	2.9	0.04
I	1	Sept. 24, 1940	20.4	.47	3.55	13.7	5.0	2.5	0.03
III	1	Sept. 26, 1940	22.6	.37	3.58	19.6†	3.9	6.1	0.02
IV	3	Sept. 29, 1940	22.9	.40	3.78	18.5†	3.0	9.3	0.11
V	2	Aug. 22, 1940	22.9	.35	3.91	19.3†	3.5	3.7	0.03
I	1	Oct. 7, 1941	23.9	.49	3.30	12.2	.47	3.0	0.05
IV	1	Sept. 17, 1941	21.7.	.41	3.57	20.6†	.36	2.2	0.07
V	1	Sept. 11, 1941	24.5	0.20	3.96	20.3†	0.41	3.3	0.07

\* Determined in a color comparator using an arbitrary color standard made from Eastman ABC dyes; the color intensity increases as the figures increase.

† Fermentation arrested or the alcohol content increased by the addition of grape brandy

‡ The fermentation of all the Orange Muscat samples was arrested by the addition of grape brandy

TABLE 16  
COMPOSITION OF MUSTS AND WINES OF RED VARIETIES PARTICULARLY RECOMMENDED FOR REGION IV

Region	Number of samples	Average harvest date, and year	Must			Wine				
			Balling degrees	Total acid, grains per 100 cc	pH	Alcohol, per cent	Fixed acid, grains per 100 cc	Extract, Tannin, grains per 100 cc	Tannin, grains per 100 cc	Color intensity*
Aleatico†										
V	1	Aug. 12, 1935	23.8	0.78	...	10.9	0.58	2.8	0.09	1R-8
IV	2	Sept. 22, 1936	25.0	.47	3.80	19.1	.35	12.8	.05	3RY-5
V	2	Aug. 12, 1936	23.0	.60	3.83	19.1	.40	11.8	.10	3RY-6
IV	1	Sept. 23, 1937	24.0	.60	3.80	18.5	.31	12.7	.04	3RY o.s.†
V	1	Sept. 24, 1937	22.4	.51	3.65	17.0	.32	11.8	.04	3RY o.s.
IV	1	Oct. 17, 1938	25.8	.55	3.42	20.0	.46	12.5	.08	3R-7
IV	2	Sept. 21, 1939	26.4	.55	3.45	19.0	.43	11.8	.05	3RY-7
IV	2	Sept. 20, 1940	24.4	.63	3.46	17.8	.40	12.8	.06	...
IV	1	Oct. 29, 1941	26.2	0.50	3.49	19.2	0.49	10.4	0.08	200
Mission‡										
I	1	Oct. 10, 1935	20.1	0.26	...	11.2	0.36	2.1	0.09	3RY-4
III	1	Oct. 2, 1935	23.1	.44	...	12.5	.38	2.0	.14	3R-10
IV	3	Sept. 26, 1935	21.4	.40	...	10.4	.35	2.2	.09	3RY-3
V	2	Sept. 11, 1935	25.0	.41	...	12.3	.33	2.3	.11	3R-4
II	1	Sept. 26, 1936	26.1	.32	4.05	17.0	.26	12.4	.07	3R-10
III	1	Oct. 2, 1936	23.6	.33	4.01	17.9	.24	11.6	.07	3RY-8
IV	3	Sept. 16, 1936	25.6	.36	4.05	16.5	.26	10.9	.05	3RY-4
V	2	Aug. 30, 1936	23.5	0.23	4.12	12.0	0.27	2.0	0.05	...

II	1	Sept. 22, 1937	23.5	0.19	3.54	20.8	0.30	3.2	0.02	..	..
III	1	Sept. 20, 1937	24.8	3.65	19.9	25	17.7	03	..	..	..
V	2	Oct. 12, 1937	25.8	.41	3.01	18.8	22	11.0	04	..	..
I	1	Oct. 21, 1938	21.8	.42	3.60	..	.34	12.9	.07	3Ry-3	37
IV	2	Oct. 10, 1938	24.1	.45	3.98	18.5	.32	18.3	.95	3Ry-5	43
I	1	Oct. 4, 1939	24.0	.53	3.30	18.0	.33	11.6	.06	3Ry-13	193
II	1	Sept. 24, 1939	21.7	.57	3.15	22.2	.34	11.2	.02	Amber	10
III	1	Sept. 22, 1939	24.0	.66	3.12	22.2	.53	12.0	.02	..	..
IV	3	Oct. 6, 1939	26.3	.47	3.71	10.4	.27	13.8	.03	3R-3	28
V	1	Sept. 26, 1939	26.9	.33	3.80	18.6	.25	13.0	.03	Amber	18
IV	3	Oct. 11, 1940	23.9.	.51	3.59	18.8	.41	13.8	.13	..	104
IV	2	Oct. 30, 1941	24.8	0.55	3.72	18.7	0.44	12.8	0.07	..	66

## Tinta Madeira§

IV	1	Sept. 23, 1935	23.0	0.53	..	10.9	0.35	1.8	0.16	5VR-13	..
IV	2	Sept. 26, 1936	27.1	.65	4.01	10.9	.45	12.5	.09	3Ry-16	322
IV	1	Oct. 7, 1937	23.7	.61	3.44	19.9	.37	10.6	.06	2R-13	139
IV	4	Oct. 10, 1938	24.3	.69	3.74	18.4	.47	12.7	.11	2VR-13	174
IV	4	Oct. 2, 1939	26.0	.52	3.71	18.0	.47	11.4	.06	..	222
IV	4	Oct. 6, 1940	23.7	.65	3.66	18.3	.39	10.7	.10	..	182
IV	3	Oct. 11, 1941	24.6	0.64	3.69	20.5	0.44	12.9	0.13	..	95

\* Data in left column, by the DuJardin-Salléron vino-colorimeter; following Hilward's procedure the observed figures have been divided into 4,000 so that the recorded figures will be proportional to intensity. Data in right column, by use of color standards and a color comparator.

† Color too light to measure.

‡ Fermentation of all samples except 1935 and region V for 1936 arrested by the addition of grape brandy.

TABLE 17  
COMPOSITION OF MUSTS AND WINES OF RED VARIETIES PARTICULARLY RECOMMENDED FOR REGION V

Region	Number of samples	Average harvest date, and year	Must			Grenache			Wine		
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol, per cent per 100 cc	Fixed acids, grams per 100 cc	Extract, Tannin, grams per 100 cc	Color intensity*	Tasting record	
I	1	Oct. 16, 1935	24.0	.53	..	0.56	2.4	0.11	5VR-11	.	Balanced, good color, flavor, becomes flat
II	2	Oct. 12, 1935	22.1	0.49	..	11.9	5.6	2.3	13	VR-23	Slightly distinct flavor, fruity; above average
III	3	Sept. 30, 1935	25.0	0.49	..	12.9	5.0	2.3	13	4VR-27	Average color, flavor, fruity; not distinctive
IV	4	Oct. 10, 1935	22.5	0.54	..	12.1	4.4	2.2	0.9	2VR-6	Lacks color; oxidized, fruity when young
V	2	Sept. 7, 1935	22.8	0.56	..	10.9	4.6	2.3	13	2VR-5	Flat; deficient in color; tends to spoil
VI	2	Sept. 22, 1936	25.1	0.51	3.92	14.7	.42	3.0	15	R-14	Medium color; very flat; poor quality. Duplicate lots produced soft, fruity, red dessert wine.
III	2	Sept. 16, 1936	23.4	0.60	3.41	11.1	5.6	2.7	10	R-10	Average flavor, color, fruity, not distinctive. Duplicate lots produced fruity but common red dessert wine.
IV	5	Oct. 5, 1936	24.9	0.45	3.74	13.7	3.4	2.7	11	2R-8	Deficient in color; flat; ordinary. Duplicate lots produced fruity, pleasing red dessert wine of good color
V	3	Aug. 30, 1936	23.3	0.38	3.95	11.9	.35	2.5	0.8	3R-5	Flat, easily oxidized; orange-pink color. Duplicate lots produced fairly fruity, tawny dessert wine.
II	2	Oct. 13, 1937	25.3	0.55	3.57	14.5	4.7	2.3	.11	VR-13	Slightly distinct; soft, smooth, alcoholic, flat
III	2	Oct. 6, 1937	25.1	0.54	3.30	14.5	5.3	2.3	10	3VR-20	Fruit, pink; ordinary quality.
IV	3	Oct. 7, 1937	25.6	0.51	3.64	13.9	3.4	2.5	.05	3VR-7	Very flat; oxidized; pink. Duplicate lots produced distinctly flavored red dessert wine of good color.
V	2	Oct. 12, 1937	24.0	0.43	3.69	20.3†	20	9.5	.03	.	Balanced, good-quality Angelica, and good sherry
I	1	Oct. 12, 1938	23.0	0.59	3.48	14.8	6.1	3.2	.	.	Fruity; distinct character, grapes overripe; alcoholic.
II	2	Oct. 28, 1938	25.6	0.55	3.18	13.3	6.3	2.4	.17	R-14	Fruity, distinct flavor, good quality. Late harvested lot produced very fruity, smooth Angelica.
III	1	Sept. 25, 1938	22.7	0.63	3.15	12.6	.64	2.4	.	.	Fairly tart, fruity; medium distinct flavor. A clean, balanced sparkling wine was produced of a duplicate lot.
IV	2	Oct. 10, 1938	22.9	0.43	3.44	12.6	0.40	2.3	0.14	R-9	Deficient in color; average table wine. Duplicate lots produced luscious, fruity Angelica.

I	2	Oct. 1, 1939	23.9	0.66	3.09	12.6	0.01	2.4	0.11	VR-17	193
II	3	Sept. 25, 1939	24.1	0.63	3.11	13.1	.67	2.5	1.3	VR-15	209
III	2	Sept. 15, 1939	24.6	0.81	2.99	13.0	.66	2.7	1.6	VR-17	233
IV	1	Sept. 15, 1939	21.6	0.72	3.05	10.8	.52	2.4	2.6	3R-5	80
V	1	Sept. 29, 1939	25.2	0.35	3.60	16.5†	.29	12.3	0.2	Amber (white)	93
I	1	Oct. 4, 1940	24.8	1.04	3.00	14.6	.79	3.1	1.5	-	244
II	1	Sept. 14, 1940	24.7	0.59	3.54	12.7	.45	2.4	1.4	-	225
III	2	Sept. 11, 1940	25.3	0.69	3.29	14.1	.64	2.0	1.6	-	236
IV	4	Sept. 21, 1940	24.9	0.59	3.49	11.7	.56	2.3	1.2	-	148
V	1	Aug. 20, 1940	25.5	0.47	3.57	16.7†	.30	16.3	1.9	-	31
III	2	Sept. 13, 1941	23.8	0.67	3.03	12.4	.02	2.7	1.8	-	249
IV	2	Sept. 6, 1941	20.8	0.67	3.12	10.3	.59	2.4	1.3	-	48
V	1	Aug. 26, 1941	26.7	0.47	3.42	21.9†	.039	14.0	0.13	-	50

III	1	Sept. 24, 1935	24.3	0.70	12.8	0.69	2.6	0.33	2YR-153	-	-
III	1	Oct. 2, 1935	21.7	0.68	10.5	.64	2.9	.25	3YR-114	-	-
V	1	Aug. 12, 1935	22.9	0.70	9.9	.77	3.6	.25	VR-100	-	-
I	1	Oct. 5, 1936	25.8	0.69	3.88	15.7	.66	3.8	.30	3YR-222	3,330
V	1	Aug. 9, 1936	21.6	0.61	11.1	.67	3.4	.33	4YR-100	5,000	-
II	1	Sept. 22, 1937	24.7	1.01	3.34	13.0	.69	3.2	.37	5YR-266	2,500
V	1	Sept. 9, 1937	24.0	0.75	3.72	10.3†	.50	9.7	.21	R-80	1,000
V	1	Oct. 3, 1938	27.8	0.54	3.96	19.9†	.55	11.4	.29	3VR-100	1,110
V	1	Aug. 30, 1939	24.7	0.64	3.72	18.6†	.65	11.0	.17	-	720
II	1	Sept. 13, 1940	25.1	0.91	3.36	20.6†	.71	10.3	1.0	-	1,316
V	1	Aug. 15, 1940	26.0	0.57	3.38	16.0†	.60	12.0	.26	-	1,630
V	1	Sept. 11, 1941	25.8	0.69	3.19	12.9	0.55	3.3	0.35	-	1,540

\* Data in left column, by the Dujardin-Salleen wine-colorimeter following Higland's procedure; the observed figures have been divided into 4,000 so that the recorded figures will be proportional to intensity. Data in right column, by use of color standards and a color comparator.

† Fermentation arrested by the addition of grape brandy.

Recommended white varieties for standard, special, or blending wines are French Colombard and Pinot blanc. Also possible but not ordinarily recommended are the Folle blanche and Peverella.

Table 13 gives the analyses of musts and wines of the recommended white varieties from various regions of California except for Sauvignon blanc and Semillon. (See tables 9 and 11.)

*Red Varieties.*—Recommended red varieties for standard, special, or blending table wines are Barbera, Carignane, and Refosco. Also possible but less desirable are Gros Manzenc and Sangioveto.

The recommended red variety, if a red dessert wine is to be produced in this region, is Trousseau.

Table 14 gives the analyses of musts and wines of the recommended red varieties except for Refosco. (See table 12.)

#### VARIETIES FOR REGION IV

The soils of region IV are usually fertile. Most vineyards there are irrigated and are capable of producing large crops. Certain vineyards of the foothills on the sides of the Sacramento and San Joaquin valleys fall, however, into this climatic zone. It is questionable whether these low-producing vineyards should be planted to grapes at all, since they cannot compete successfully with the fertile, irrigated valley soils. Bioletti<sup>35</sup> summarized the recommendations for these foothill regions in the report for 1895-96 and 1896-97. The lack of production and the temperature conditions prevent the production of high-quality table wines or of cheap blending wines. That superior dessert wines might be produced was a possibility in his opinion.

Although natural sweet wines are possible here, in warm years the suitable grapes will become sunburned and raisined. White dessert wines can be produced, however, as well as good red dessert wines. The standard white and red table wines from this district are fairly satisfactory if produced from high-acid varieties.

*White Varieties.*—The recommended white variety for standard-quality table wine is the French Colombard. Peverella is also possible. (See p. 543 and 574.)

Recommended varieties for muscatels include Malvasia bianca, Muscat Canelli, and Orange Muscat.

Recommended varieties for white dessert wines are Mission, Palomino, and Verdelho.

Table 15 gives analyses of musts and wines of the recommended white varieties from various regions, except for the Muscat Canelli and French Colombard (table 13) and for Mission, a red variety (table 16).

*Red Varieties.*—The recommended red variety for standard table wine is Barbera. Also possible but less desirable are Grignolino (for pink wines) and Gros Manzenc.

Recommended red varieties for bulk-quality table wines are Carignane and Refosco. Valdepeñas is useful but has certain deficiencies.

Recommended red varieties for dessert wines are Tinta Madeira and Trousseau. The Tinta Cao is nearly as good and may sometimes be planted in place of the Trousseau. The Aleatico is recommended for muscatel.

<sup>35</sup> See citation in footnote 17, p. 496.

Table 16 gives analyses of musts and wines of the recommended red varieties from various regions of California, except for the Barbera, Carignane, Riesco, and Rousseau, for which see table 14.

#### VARIETIES FOR REGION V

Region V is the hottest section where wine grapes are grown in the state. It is likewise the most uniformly fertile. Except for a few vineyards near Redding, and some in the lower foothills, the district is entirely in the highly productive, irrigated central valleys. Bulk-quality red table wines can be produced from the higher acid varieties, but white table wines should not be attempted on account of the warm storage conditions and the necessity for maintaining a high sulfur dioxide content in order to keep the color sufficiently light. Region IV vineyards are better adapted for producing bulk red table wines; region III white table wines. Very good white and red dessert wines can be produced.

*White Varieties.*—Recommended varieties for muscats are Malvasia bianca and Orange Muscat. The Muscat Canelli is a possibility, but it is a weak grower under these conditions and the fruit frequently sunburns badly.

Recommended varieties for white dessert wines are Palomino, Mission, and Grenache. Analyses of Malvasia bianca, Orange Muscat, and Palomino, have been given in table 15. The analyses of the musts and wines of the Mission are given in table 16 and those of Grenache in table 17.

*Red Varieties.*—Recommended varieties for red dessert wines are Rousseau (although preferably planted in III and IV) and Tinta Madeira (table 16). Tinta Cao is also practicable. Black Malvoisie may be useful because of possible dual use as a shipping grape, but is not recommended.

A recommended variety for special or blending wines is Salvador. Analyses of its musts and wines are given in table 17.

#### NOTES ON RECOMMENDED WHITE VARIETIES

*Chardonnay.*—The Chardonnay is supposed to be a white variation of the Pinot noir, which it resembles in several respects. The young shoots, tendrils, and leaf stalks are of almost identical coloring—bright, glossy green, and reddish-brown on the exposed side. The hairy coating on various parts of the two varieties is also similar in character and amount. This is the variety from which are produced the famous white Burgundy wines of France.

Chardonnay differs from the Pinot blanc, a variety with which it is often confused, in both fruit and vegetative characters. It shows considerable color on the shoots and other parts, as indicated above, whereas Pinot blanc lacks conspicuous color except at the nodes. The hairy coating on the Pinot blanc leaves, too, is much heavier, persisting on the underside of the mature leaves as tufts of matted hairs, while the underside of the Chardonnay leaves are glossy green, with only an occasional long hair. In many leaves of Chardonnay the two lower primary veins are naked or tend to be naked from their attachment on the petiole to their first branch along the side next to the petiolar sinus. In the Pinot blanc a marginal strip of leaf tissue covers these primary veins, as in most varieties. Pinot blanc clusters are small, conical, and compact, while Chardonnay are small, conical-cylindrical, and loose to well filled. The Chardonnay ripens a week to 10 days earlier than Pinot blanc.

The Chardonnay, a vigorous grower, is only a moderate producer. During the early years in the vineyard its vines are less productive than the Pinot blanc; but as they increase in size and develop a large bearing surface, they are equally or more productive. The unfavorable bearing habit can be largely corrected by the pruning system discussed for Cabernet Sauvignon (p. 553).

The clusters of Chardonnay, as indicated above, are loose to well filled. The berries are small and firm, with a thick, tough skin. They are resistant to unfavorable weather conditions and handling injuries, but the juice yield is only moderate.

When harvested at normal maturity for the production of dry table wines, the musts were well balanced. They retained a favorable acid content, and the pH of those from regions I and III was relatively low.

The Chardonnay wines from properly matured fruit of regions I and III were excellent—distinctive in aroma and flavor, rich, smooth, well balanced, superb in finish. They revealed most of the properties of this variety to excellent advantage. They developed normally and cleared rapidly. After attaining maturity, they kept very well.

The Chardonnay wines of region IV, though still distinct in aroma and flavor, were less harmonious, somewhat flat, and lacking in finish. These were only average table wines.

This grape is well adapted to regions I and II. There it will set well and at maturity will possess the rich, pronounced flavor and other properties of the variety. Good wines have been produced of it in region III; though great care is necessary to time the harvest in order to secure the qualities at their best without permitting the acid to drop too low or the pH to go too high. Nowhere, in fact, should the Chardonnay be planted by any one not prepared for great effort in its production, harvesting, vinification, and aging.

It should not be planted in regions IV and V as it does not produce sufficiently good wines to compete with more productive sorts.

*Folle blanche*.—Until the advent of the phylloxera the Folle blanche was the principal grape of the Charantes region of France. Its use in brandy making is well known.

Wherever the Folle blanche has been grown in California it has produced well. The vines are vigorous, their short thick canes remaining upright. The clusters are medium-large, short-conical, and compactly set with medium-sized, round berries. The leaves are dull green and five-lobed, with cobwebby tomentum below and a few long hairs above. The fruit matures without rotting in dry years, but is unfortunately susceptible to bunch rot in humid regions or seasons. The grapes are easily crushed, and the juice yield is satisfactory.

Regardless of the region, the musts and wines of this variety have been well supplied with acid, almost without exception. As a result, the wines have a tartness all too uncommon in California wines. Generally they have been light, fruity, pleasant, soft, very clean and refreshing, but with only a mild distinctiveness. Their quality has been average to good, but never outstanding. Their slight distinctiveness, together with their tartness, freshness, and freedom from objectionable properties, is their principal value. When the grapes are grown in a suitable location, the product may be aged into a table wine

well above average. It is also a good stock for California white sparkling wine, or in blending may lend acidity and freshness to wines of more quality and character but less acidity.

Wetmore and the California Viticultural Commission<sup>26</sup> were much impressed with the possibility of Folle blanche wine for beverage brandy. The grapes tested, however, came from region II or III. Although there is only a limited amount of data regarding the brandy, plantings in region IV or V do not seem a happy choice. Even so, the brandy will surely be better than that of neutral very low-acid varieties.

Folle blanche is recommended for regions II and III. It may be planted in I for blending wines only. Small plantings for beverage brandy tests are recommended for regions I, II, and III.

*French Colombard.*—This variety was introduced to California viticulture by Mr. George West. Apparently its European connections were not established at that time, so it was known as West's Prolific in the rather wide distribution it attained, especially in region IV, prior to the adoption of national Prohibition. Since its fruit did not meet the shipping requirements of the dry era, all of these early plantings were either grafted to other varieties or uprooted.

Late in the Prohibition period this variety was discovered as occasional mixes in a black-wine-grape vineyard in the Lodi area. Its European identity was still unknown, so when Mr. L. K. Marshall, who recognized its promise, reintroduced the variety, he named it Winkler. Recently it was shown that this variety is the French Colombard. This name identifies the variety as of great importance in France for the production of brandy, especially in the Cognac region, and gives some indication of what might be expected of it in California.

The vines of this variety are very vigorous and productive. At Davis it has outyielded Green Hungarian and has almost equaled Burger. Its clusters are medium-large, long-conical, well filled with medium-sized, short-oval berries. The fruit ripens about midseason and has regularly reached the crusher in good condition.

In order to better portray the place of this interesting variety, the results of twenty-two lots of wine produced by Hilgard<sup>27</sup> will be utilized along with those of the present investigations. Hilgard produced lots of wine as follows: nine from region II, six from region IV, and seven from region V.

This variety has been outstanding in retaining a high degree of acidity at full maturity in the warmer regions. Its pH has been very low. The general balance of its musts has fitted them unusually well for producing dry table wines in region IV. These wines have been distinct in aroma, fairly full and pleasing in flavor, tart, refreshing, and well balanced. Their finish, too, has been rather good. For this area of production, they have shown exceptional balance and quality. Although not so full and harmonious as the Pinots or the Sylvaner, they have ranked well above the average as table wines.

There was little difference in the balance of the musts of the French Colom-

<sup>26</sup> Wetmore, C. J. Grapes suitable for fine brandy. p. 12-14. In: Brandy distillation. Appendix A to the Biennial Report of the Board of State Viticultural Commissioners for 1891-92. 125 p. California State Printing Office, Sacramento, Calif. 1892.

<sup>27</sup> See citation in footnote 16, p. 496.

bard grown in the different regions. Though the wines of the cooler regions were a bit lighter and slightly more delicate, the difference was minimal when compared with that of most of the other varieties. The wines of the French Colombard do not show up so well by comparison with the better varieties in the cooler regions as they do in region IV.

These wines have fermented unusually well and have been singularly free of difficulties while aging. They have matured relatively rapidly, and kept well.

In region IV French Colombard will be of value in its own right for producing standard-quality table wines as well as for blending to improve the balance of the products of other more highly flavored but flatter varieties. Its wines are too tart and do not possess sufficient finish to compete with those of the better varieties adapted to regions I and II. Although the French Colombard is adapted to region III, further tests should be made to determine its relative value here and its possibilities in region V. It is not recommended for dry table wines in regions I and II. Its possibilities for beverage brandy production are being tested.

*Malvasia bianca*.—*Malvasia bianca* is a muscat-flavored variety, ripening in midseason. At Davis it has been a moderate producer. When overcropped, however, it does not ripen till very late in the season. The clusters are large, closely set with medium to large berries. The skin is fairly thick, and the grapes remain on the vines in good condition until late. Unlike the Muscat of Alexandria, the fruit matures evenly and does not raisin while ripening, although sunburn may occur. The grapes are easily crushed, and the juice yield is good. The flavor is a distinct but delicate muscat.

This variety has been tested in regions III, IV, and V. The musts have more acidity than those of Muscat of Alexandria, although in regions IV and V they are usually too deficient for dry or natural sweet table wines. The samples from region III, however, appear well balanced and might serve for the latter purpose. Unfortunately, the flavor is like that of the other muscat varieties: the dry wines are rather harsh, but seem to be more fruity and to have a cleaner fermentation.

The dessert wines appear more promising, since they are uniformly distinct in muscat aroma, have no raisin or overripe grape taste, and possess a fruity, well-balanced character.

Hilgard tested this variety and found it to have a rich delicate muscat flavor. Although Bioletti did not recommend it, he did not recommend any muscat-flavored variety; so his omission is not significant. (Bioletti did mention the Muscat of Alexandria for the production of raisins; and for the San Joaquin Valley foothills he regards<sup>28</sup> *Malvasia bianca* as being "very suitable for the production of a delicate sweet muscat.")

The *Malvasia bianca* is recommended only in regions IV and V, where it will produce white muscatel. Plantings should be restricted in view of the competition of the present large acreage of Muscat of Alexandria, and also because the demand for muscat-flavored varieties may very well not be maintained if a more critical dessert-wine market develops in America. Small plantings, destined to supplement present acreages, would nevertheless be desirable, since the wine is above average in quality. The present recommenda-

<sup>28</sup> See citation in footnote 17, p. 496.

tion for muscatel is to plant Malvasia bianca or Orange Muscat and Muscat Canelli. The latter variety, though not a good producer, has the most desirable flavor. The flavor of the Malvasia bianca is good, and its yields are regular.

*Muscat Canelli*.—Muscat Canelli is probably the same as Muscat de Frontignon. Under these two names it has won renown abroad as the variety from which are produced the Asti Spumanti wines of Italy and the best-known French muscatels.

The vines are only average in vigor and moderate in productivity. The planting distances should be reduced. The clusters are medium-large, long-conical, and well filled with medium-large berries. The juice yield is average or slightly above. The berries withstand raisining much better than those of the Muscat of Alexandria and are also more resistant to handling injuries. They ripen before the latter variety, however, and if left on the vines until midseason will raisin badly.

Consistently, the musts and wines of the Muscat Canelli have had more acid than those of the Muscat of Alexandria. This property alone has improved its wines. Although improvement in cleanliness of fermentation is perhaps most important, the flavor is also better. Its wines do not have the marked harshness found in those of the Muscat of Alexandria.

The dry wines of this variety have been only average, but still they have been among the best of this type. While young they have been rich in the muscat aroma, and this property was retained in considerable quantity into the second and sometimes the third and fourth years. In addition, these wines have been full flavored, fairly smooth, and fairly well balanced.

The dessert wines have been heavily perfumed, richly flavored, luscious, smooth, well balanced, good to excellent in quality for the type. For these wines the Muscat Canelli ranks among the best of the many muscat varieties.

This variety has produced wines of good to very good quality in regions II, III, IV, and V. It is best adapted to III and IV, where it attains full maturity every year and its aroma and flavor are at their best.

In region V the fruit is somewhat subject to sunburn, since the vines are not vigorous and their growth is not dense. In cool seasons in region II the fruit may not ripen completely. This variety should be considered only because of its potentialities for quality sweet wines. Either natural sweet or dessert wines may be produced from it. Sweet sparkling wines with a muscat flavor have not had sufficient popularity to warrant extensive plantings of this variety.

*Orange Muscat*.—The Orange Muscat, a recent introduction, is both vigorous and productive. The clusters are medium-large; the berries irregular, varying from large to very small. The irregularity in size is of little importance for wine production, though somewhat undesirable in table grapes. The skin is thick, and the berries rather hard. The grapes are only moderately easy to crush, and the juice yield is below average. The grapes ripen evenly and normally, reach the crusher in a very clean condition, free of rot and, compared to other muscat varieties, relatively free of sunburn and raisining.

The wines are rich in muscat aroma, with a full, soft, luscious, and distinctive muscat character. In this respect it is among the strongest and most pleasant of the muscats. In regions IV and V these wines have been more delicate and better finished than those from Muscat of Alexandria. They are

not equal to Muscat Canelli, and are somewhat different in character from it. The aroma is more flowery than that of the other white muscat varieties.

The Orange Muscat should find a place for itself, especially in region IV, and in region V when the purpose of planting a muscat is solely for wine production. (See p. 574 for further comments on muscat-flavored wines.) It is more productive than Muscat Canelli and does not suffer the sunburn of the latter. It will not regularly ripen in the cooler regions.

*Palomino*.—Its great vigor and productivity have made the Palomino a favorite white variety with many California growers. The clusters are very large, with round to "vertically flattened" (oblate) berries. The skin is thick and moderately tough. Pressure between thumb and finger reveals the rubbery texture. Because of its open cluster structure, its thick, tough skin, and the firm texture of its pulp, this variety is relatively resistant to unfavorable weather, though mildew may cause some damage. The tough skin and firm texture, however, impede satisfactory crushing; and the juice yields are much below average.

The dry table wines from the Palomino grapes of all regions have, without exception, been disappointing. Their flavor has a typical harsh character, which in the dry wines is especially coarse and unpleasant. Even in the coolest locations the acid content of the mature fruit is deficient for producing a balanced table wine. This deficiency has caused most of the wines to be flat and easily oxidized.

The composition of the must indicates the suitability of ripe Palomino for dessert wines. Regularly, except when overcropped, it attains a high percentage of sugar; and it never contains more than moderate amounts of acid. Appropriate wines from regions III, IV, and V, when baked or treated with film yeast, have produced good to very good sherries—well balanced, soft, pleasant, and typical in flavor and aroma according to the method of production.

On the basis of its vigor and productiveness the Palomino, under the erroneous name of Napa Golden Chasselas, has been widely planted in coastal counties. Since, however, the dry wines of this variety have never possessed more than ordinary quality, it should not be planted in regions I and II. Furthermore, the plantings already located there should be converted to better dry white table wine grapes.

For sherry in regions IV and V, no single variety equals the Palomino. It responds more favorably to baking than any of the other varieties tested. Its greatest value is in the production of dry, delicate, lighter sherries; yet the sweet heavy types profit by generous percentages of Palomino.

*Pinot blanc*.—The Pinot blanc is grown extensively in certain sections of France. From it the Chablis wines derive their characteristic properties. (For comparison with Chardonnay, see p. 541.)

The vines are somewhat below average in vigor, and moderately productive. The clusters are small, conical, compactly set with small, round, firm berries. The skin is fairly tough. Because of the compactness this variety is not very resistant to unfavorable weather conditions. Rains or foggy, damp weather may cause rot. It resists handling injuries very well.

The musts of normally matured fruit from regions I and III were not particularly well balanced for table-wine production. They have tended to be

somewhat low in acid and high in pH. The musts from regions IV and V have been too low in acid and too high in pH, except when the fruit was picked very early.

The Pinot blanc wines from regions I and III were distinct in aroma and flavor, smooth, fairly well balanced, of good finish. The quality was good. Most of the varietal characteristics except acidity were well displayed. The wines cleared normally and kept well.

The wines from regions IV and V made from this variety were generally unsatisfactory. Though of good aroma and flavor, they were flat and only fairly well balanced, with a marked tendency to oxidize. The deficiency in acidity was their main defect. Earlier harvesting that retained a higher per cent of acidity improved the quality of wines of region IV considerably, but still they were only average.

The Pinot blanc is adapted to the warmer parts of region I and to region II. In areas where it will not mature until very late, the loss from rot will be excessive. In the warmer areas, such as region III, the acid content will tend to be low at normal maturity.

This variety is not adapted to regions IV and V. Here the quality will not be high enough to offset the relatively low yields.

*Sauvignon blanc*.—The Sauvignon blanc is a rather poor producer unless pruned long. The small clusters are closely set with medium-sized oval berries, which have a moderately tender skin and should therefore reach the winery as soon as possible after harvesting. The small-sized clusters and the small crops make this grape expensive to harvest as well as to grow. The flavor is usually distinct and aromatic. The juice yield is average.

Because of its low production, the Sauvignon blanc should be considered only for the best-quality wines. It has been tested in all the regions of California. It ripens fairly early and if harvested by midseason retains a fair degree of acidity. The distinctive flavor is carried over and even increased in the wine, whether the grapes are produced in the coolest or the warmest region. If harvested before full maturity, however, the fruit has a much less distinctive flavor. Irrespective of the year and the region there seems always to be an overabundance of sugar. The better-quality wines came from regions I and II, although very good wines were produced in III. The distinct aromatic flavor is so strong that in some regions and years it may have to be blended with a more neutral-flavored variety to achieve consumer acceptance. It should not, however, be diluted too much. The possibility of using Sauvignon blanc for natural sweet wines should be more widely investigated, particularly in warm seasons and in region III. The high degree of sugar achieved without undue raisining makes it suited for this type of wine.

The Sauvignon blanc is recommended in regions I, II, and III for producing quality wines either by itself or by blending. In addition, in region III it is recommended as a constituent of natural sweet wines. This agrees in general with Hilgard and Bioletti, who recognized its high quality.

*Semillon*.—The Semillon is the most important grape of the Sauternes region in France, where its fruit accounts for about 75 per cent of the production. The wines of the Graves also contain a large percentage of this grape, from which they derive their fullness.

Semillon vines are above the average in vigor and productivity. The clusters are medium-large, conical, compact, and often winged. The berries are medium-sized, round, yellow-green, with a rather tender skin. In poor soils or dry years they are smaller. Very ripe grapes have a slight pinkish tinge—not sufficient, however, to color the must. If the vines are overcropped, the Semillon does not ripen properly and may even shrivel before reaching 20° Balling. For this reason it should seldom be cane-pruned. It must be handled with care and without delay. Fruit of advanced maturity is very susceptible to rain damage. Small cracks occur in which molds grow rapidly, especially the harmful *Penicillium*.

In general the musts are better suited for natural sweet rather than dry table wines. Their acidity is too low for the latter except in the cooler seasons of region I. Then, too, the character and flavor are more pleasing in a wine that retains some sugar. Dry wines produced from Semillon, even in the cooler regions, are frequently heavy, slightly harsh, and somewhat unharmonious.

The wines from regions II and III were characterized by a balance of their properties that places them among the superior wines of our state. Some had a smoothness, body, flavor, and richness of aroma that the Semillon alone can give and then only when planted in an ideal environment. Allowing for the absence of the complement to the aroma and flavor resulting from the *Botrytis cinerea* abroad, as we must do under our very dry autumns, these wines were gratifyingly typical of this variety. Only those that retained an appreciable amount of sugar reached this high quality. In these regions the acidity was regularly too low for balanced dry table wines.

In region IV the natural sweet wines of the Semillon do not equal those of regions II and III in delicacy and balance. They were regularly somewhat heavy, their aroma and flavor were stronger, but less delicate, and the acid was lower. Nevertheless, many showed real quality and were among the best wines of this area.

In region V the wines were generally heavy, coarse, and flat. Raisining was a serious problem.

The Semillon cannot be recommended for region I. There the wines are only average or slightly better than average. The vines are susceptible to mildew, and their fruit will rot badly in years of early rainfall. Production is relatively low and irregular.

This variety comes into its own on the appropriate soils of regions II and III. Time may tend to indicate special locations, though many of the differences now supposed to exist arise more definitely from the handling of vines and fruit and from vinification than from the local areas of production. The reputation of the Semillon from the rocky soils of the Livermore Valley is, however, probably based on a real difference in quality: these wines are said to be more aromatic than those produced at similar temperatures in the Napa Valley. Since the poor and rocky soils of Livermore do not support such a large vegetation and cropping as the rich mid-valley alluvial soils of the Napa Valley, the Livermore vines seldom overcrop and consequently attain a high degree of sugar. Possibly also the average berry is smaller, with a greater relation of surface to volume; the skin contains more of the aroma-producing substances. In these regions there is sufficient heat to mature the crop, yet not

enough heat to cause serious difficulties in harvesting and handling. Here the production is good for the variety, and mildew can be controlled in all seasons.

Although less well adapted to region IV than to regions II and III, the Semillon under suitable cultural operations, timely harvesting, and prompt and proper vinification procedures will produce a very acceptable natural sweet table wine in this environment. The individuals and firms interested in producing a good natural sweet table wine in this region may well consider the Semillon. It will produce good crops; and unless unsound and raisined fruit is permitted to enter the crusher, the product will be creditable.

The Semillon is not adapted to region V; here it tends to sunburn, and considerable raisining occurs.

*Sylvaner*.—The Sylvaner ranks second among the varieties of central Europe, where it produces above-average wines under a range of conditions. In our state it is sometimes erroneously called Franken Riesling.

The vines, of medium vigor, are productive. Its almost entire, medium-sized, round, yellow-green, hairless leaves are an aid in identification. The clusters are small to medium, cylindrical, compact, and usually winged. The berries, small-medium, round, dark bluish-green to yellow-green, show prominent corky dots. Although the skin is relatively thick, it is tender and requires careful handling. Early rains may cause considerable rot. Prompt moving from the vines to the crusher is very important. The grapes crush easily, and the juice yield is satisfactory.

Sylvaner commences growth somewhat later than most varieties in spring. This fact may reduce the frost hazard. Still, the fruit matures relatively early. It is rather susceptible to mildew.

The musts have shown unusual uniformity of composition in the different regions from which fruit was obtained. The failure to show a higher degree of acidity in the cooler locations was due, no doubt, to a more advanced stage of maturity of the fruit in these regions at the time it was harvested; but the variety is one of restricted acidity at best. In general, the must was somewhat low in acid for the production of superior wines. This defect can be overcome somewhat by more careful timing of the harvest. (See table 11 for must composition for 1939, 1940, and 1941.)

The wines from regions I and II possessed a very delicate and distinct varietal aroma and flavor. Although fuller and less delicate in these respects, the wines of regions III and IV were still typical of the variety. In fact, the loss in quality and richness with increasing heat of the producing region was less marked in Sylvaner than in most of the other good varieties. Under the best conditions these wines revealed the potentialities of the variety. Many of the lots have run remarkably true to type. This finding was not entirely unexpected for the Sylvaner; of the better varieties of central Europe, it has proved to be the best adapted to warm locations.

Although the Sylvaner produces rich, delicately flavored, well-balanced wines in region I, it cannot be recommended for planting there. Under the prevailing climatic conditions the vines will be very susceptible to mildew, and the fruit will rot badly in years of early rains. In protected locations of limited area, however, the mildew may perhaps not be such a handicap.

The Sylvaner is very well adapted to region II and the cooler parts of III.

Under the conditions of these areas it can potentially produce with regularity its best California wines, provided it is harvested at the proper time. Mildew can be controlled effectively, and in most years the fruit will be mature before the earliest rain. The heavy soils of the more coastal valley floors are not best, however, for Sylvaner. In these soils it overcrops and has considerable bunch rot, particularly in cool, humid seasons.

In the warmer parts of region III and in region IV the quality of the wine, although good in many seasons, will not be sufficiently high and uniform to offset the lower yields and reduced acidity. The Sylvaner may succeed in special locations when the producer utilizes it to best advantage. In general, however, the more productive sorts such as Semillon and Folle blanche should be chosen for region III and the bulk sorts for IV.

Sylvaner has no place in region V.

*White Riesling*—The White Riesling is among the most famous white wine varieties. Its product, the Riesling wines of Germany, has a reputation equal to that of the Sauternes and White Burgundies of France and the Tokays of Hungary. It is grown only on a limited scale in California, where it has usually been called Johannisberger Riesling. This appears to be a serious misnomer, since there is no such variety abroad and since it breaks the direct ties with the famous products of the White Riesling in Germany.

The vines, above average in vigor, are about average in production. Because of the size of the clusters the vines should be cane-pruned as directed for Cabernet Sauvignon (see p. 553) if full crops are to be produced. The clusters are small, cylindrical, winged, well-filled to compactly set with small, round, greenish-yellow berries. Since the skin is fairly thick and moderately tough, the berries resist rains and unfavorable weather. They also resist handling injuries, but should be crushed without delay if the rich, delicate aroma is to be carried over into the wine without impairment.

The distribution in Europe indicates that White Riesling is well adapted to a cool climate. This is supported by the results of this study. In no California region from which this variety was obtained was the must sufficiently well balanced for an outstanding wine. The usual deficiencies were those attending insufficient acidity.

The fruit of region II, however, has had a relatively favorable acid content. Its products were distinct in aroma and pleasant in flavor, soft, and of good quality. They did not possess, however, the balance, richness, or delicacy of the best Riesling wines.

The wines from regions III and IV possessed the properties of the variety, but the proportions were even less harmonious than for region II. Aroma and flavor were poorer, and the acidity was definitely low. Despite these deficiencies, these wines were rated as average to good. This fact speaks well for the unusual potentialities of White Riesling for producing quality wines. It is not, however, an indication of adaptation to the environment. The results to date indicate that White Riesling should be grown in the coolest areas of our present grape-producing regions. This statement agrees with Professor Hilgard's findings and with pre-Prohibition experience. The variety should produce superior wines in region I, where the product retains in marked degree the qualities that have made it famous in Europe.

Further tests should be undertaken to establish the relative merits of the cooler regions and to find localities where these wines approach the highest quality attainable by the variety.

White Riesling produces fairly well in region II; but its wines, although above average, lack the balance, finish, and character that may be expected. It could be recommended only for the cooler locations in this region. Significantly, Biotelli in 1907 failed to recommend it for California. His recommendations for the coast counties were presumably for regions II and III.

Neither its productivity nor the quality of its wine commend the White Riesling for regions III and IV or for warmer localities, where the product at best will be only good table wine. The warmer the region the poorer are the wines. Other varieties such as the Semillon and Sauvignon blanc should supplement it in region III.

#### NOTES ON RECOMMENDED RED VARIETIES

*Aleatico*.—In Italy this variety is used for natural sweet wines of the *vino santo* type. Sometimes in Tuscany the grapes are hung on strings and allowed to partially dry in order to secure a very high concentration of sugar. The clusters are rather long and above medium in size. The grapes are round, of medium size, and have a distinct muscat flavor. They ripen in midseason and will raisin if left on the vines after maturity.

The Balling-acid ratios of the musts average over 44, indicating that they are well suited for dessert wines. Except in a single 1935 sample the total acid content is medium or low. The degree Balling was seldom high, largely because of the exceptionally early picking that was practiced. Harvesting and picking present no particular problems. The grapes, being fairly easily bruised, must be picked carefully. They stem without difficulty, and all of the berries are easy to crush. Despite the low total acid content, no difficulty was experienced in the fermentations. Grapes from irrigated vineyards, however, may have considerable rot.

All but two of the samples were utilized for the production of dessert wines. The total acids show a marked reduction following fermentation and the addition of grape brandy, which is natural but seems more pronounced than in some other varieties. The tannin content of the two dry samples was low, and that of the sweet wines was very much reduced. The color content likewise was very deficient compared to commercial types of red sweet dessert wines. During aging the color becomes more of an amber than a red, and in one case a completely amber wine was produced from this variety.

The tasting record indicates that the dry red muscats in general are unsatisfactory, characteristically harsh in taste. No such objection was noticed in the sweet wines. Although typically aromatic like a muscat, the wine has a perfumed character not found in other muscat varieties.

The Aleatico is not suited for dry muscat-flavored wines in the warmer districts of California and presumably will also not be sufficiently well balanced when grown in the cooler districts to produce a natural sweet wine. Hilgard, however, reports good acidity from grapes in region II; and further tests should be made in II and III. Its place is mainly for a sweet table, or sweet dessert wine in regions IV, V, and possibly III. The most serious defect is

poor color; dessert wines of this variety are too light in color. Natural sweet wines of low color content may, however, be satisfactorily produced; and the product may be blended to produce full-colored wines. Blending is not recommended, since the typical perfumed aroma, a principal merit of the variety, would be diluted by the practice. Small plantings are recommended in regions IV and V for those with a market for a distinctively flavored red muscatel. Bioletti<sup>39</sup> recommended the Aleatico for making a good red muscatel in the San Joaquin Valley.

*Barbera*.—The Barbera is known the world over because of the Italian wines of that name. Besides showing a pronounced varietal character these wines have usually—not altogether to their credit—been characteristically Italian. The roughness and gassiness of the Barbera made abroad are not, however, necessary features of its wines.

The Barbera is well above average in vigor and produces moderately well. According to Hilgard it produced about 5 tons per acre at Tulare on sandy soil. Vineyards observed in recent years have been more variable in production. Some old vineyards on poor soils have had a very small production. The vines leaf out relatively late, and show fair resistance to mildew.

The clusters are large-medium, conico-cylindrical, well filled with long-oval, large-medium, firm, black berries. Since the skin is thick and relatively tough, the fruit usually reaches the crusher in good condition. The juice yields are good. If left on the vines until late in the season, the grapes shrivel and smaller yields are obtained.

The musts have consistently shown a relatively high acidity. The degree of acidity appeared to be affected less by maturity and by region of production than in most varieties. One lot from region III at 28° and another at 25.6° Balling still contained 0.63 and 1.07 per cent, respectively, of acid, and a sample at 22.0° Balling from region V contained 0.81 per cent.

As in their native country, the Barbera wines of California have been robust and somewhat heavy. The extract has varied from 2.6 to 3.2, with little to no sugar present.

As a rule the wines have been distinctive in aroma and flavor, fruity, medium to high in acidity, average to good in character, full-bodied, and usually good in color and finish. (Since the identity of the grapes of region II is questionable, their wine will not be considered.) The wines of this variety in region III have been the most balanced in character. In the warmer regions (IV, and more particularly V), the wines were less delicate, somewhat poorer balanced, heavier, and generally lower in quality. In the latter regions the color was sometimes deficient. None of the wines have been above normal in tannin content, all being lower than most of the other well-known Italian varieties in this respect.

Because of their general character of heavy body, high acidity, and at least average tannin content the wines of Barbera require aging and greatly profit by it. After reaching full development they maintain their characteristics and quality under favorable storage conditions.

The Barbera will not ripen normally year after year in region I, and even when it does mature it will be excessively acid. The same would be true to a

<sup>39</sup> See citation in footnote 17, p. 496.

degree in region II and in all but the warmer parts of region III. In III and IV the variety offers real promise. Here it is productive, ripens well, produces a good to superior wine of pronounced varietal character, and is one of a few varieties that possess relatively high acidity when fully mature. It is among the best varieties tested for the production of average- and above-average-quality dry table wines in region V, but its planting is less well indicated for that region than for III and IV.

*Cabernet Sauvignon*.—The Cabernet wines of the world take their name from the two very closely allied varieties, the Cabernet franc and the Cabernet Sauvignon. These possess a specific color, a distinctive flavor, and a particularly intense aroma. In a favorable environment they transmit their qualities so that the wine is very distinctive. They—in particular the Cabernet Sauvignon—have given the clarets of France the character and qualities that make them one of the two most esteemed of all red wines.

The Cabernet Sauvignon is among the most vigorous of vines. With proper pruning, it is a moderate bearer. During the early life of the vines, canes should be retained in addition to spurs. After the vines attain considerable size (in eight to twelve years), spurs alone may provide sufficient bearing surface. Since the clusters are medium-small, a large number must be grown for approximately normal crops. With proper pruning the crop was increased over the spur-pruned vines by 10.3, 5.3, and 0.0 pounds to a vine, respectively, in the fourth, sixth, and eighth years at Davis. By the eighth year the vines spur-pruned from the start were so large that their bearing surface could produce full crops. From then on, the production of the spur-pruned and combined spur- and cane-pruned vines has been about equal. If the cane pruning is to be stopped after eight or ten years, the spurs must be developed along with the canes to give the vines spread and bearing surface. As the vines become larger, the canes are reduced in number or length or both as more and more fruit is produced on the spurs.

Although the system described above is the most economical for handling varieties with small clusters, no supports being required after eight or ten years, these vines can be cane-pruned throughout their life. Several successful vineyards of this variety in regions II and III are cane-pruned.

The clusters are medium to small, long-conical, loosely filled with small, round, tough-skinned, black berries that adhere firmly to the pedicels. Because of these latter properties the fruit withstands unfavorable weather with very little spoilage. It is not so readily crushed as most of the other less resistant sorts. If the grapes become overripe there may be considerable difficulty in securing adequate crushing.

The Cabernet Sauvignon grapes grown in regions I, II, and III prove well suited for table wines of superior quality. When this fruit was harvested at proper maturity the wines were distinctive in aroma, full flavored, soft, well balanced, excellent in quality. As a rule they have been genuinely typical of this variety at its best. They possessed sufficient natural acidity, normal tannin content, and good color. Earlier criticism that the Cabernet wines of California are excessively tannic should have been directed at the methods of vinification and not at the variety.

These wines require aging in the wood to permit them to mellow down and

to change the undue aromatic pungency of their youth to the pronounced but highly esteemed character of the mature Cabernet. Aging alone achieves the ultimate superb balance that distinguishes these wines. The Cabernets from suitable environments in California are no exception; they profit greatly by aging. Once matured properly, they keep unusually well.

When the grapes in regions II and III were permitted to become overripe, the acid was much reduced; the wines were less well balanced. They became heavy table wines with character and flavor, and above-average quality. A Cabernet Sauvignon of 24° Balling in these latter regions is usually overripe.

The grapes of this variety from regions IV and V do not produce a satisfactory table wine. The wines have consistently been deficient in acid, and therefore flat, lacking in freshness, and not delicate in aroma. They are, for the most part, only heavy wines of ordinary quality. Occasionally, in cool seasons, they have approached the true character and deserved a rating of good.

The Cabernet Sauvignon ranks first in the production of high-quality red table wines in California. When quality alone is considered in the planning of new plantings of red varieties, the Cabernet Sauvignon usually heads the list for regions I, II, and III.

Its wines will not bear dilution without some loss of character. To be called Cabernet a wine should, on the basis of these investigations, contain 75 per cent or more of Cabernet Sauvignon grapes. The practice of permitting the variety to get overripe and then diluting its must with some other variety of low sugar content is not recommended.

Since the Cabernet Sauvignon will not produce a distinguished wine in regions IV and V, it should not be planted there.

*Carignane*.—In the early work of the University in enology, thirty-three wines were produced of Carignane grapes from a number of locations. The results were somewhat discordant. In several favorable areas these wines were good, but in most localities they were only fair to poor. Best results were obtained on the well-drained soils in parts of the Santa Clara and upper Russian River valleys. In 1907, however, Bioletti omitted the Carignane from his recommendations. Nevertheless, the variety has been very widely planted.

The popularity of this variety has been stimulated by its great vigor and productivity. Its very upright habit of growth, which simplifies the training, has also been a factor. The most serious weakness is susceptibility to mildew: usually it requires one to several more sulfur dustings than most of the other varieties, and failure to control the mildew may result in considerable loss in crop.

The Carignane cluster is medium to large, conical, sometimes shouldered, well filled with medium-sized, oval, thick-skinned, black berries. The fruit is firm and ships well—a quality at least partly responsible for the planting of about 20,000 acres in the period 1920 to 1930. The fruit is crushed without difficulty.

Carignane in regions I and II is usually fairly well balanced for table wines. In warm seasons the acid content may be low, and the color deficient. On the whole, however, the products have been sound, fruity, well-balanced table wines of good-average quality. They are pleasant, though not one could be considered to be a quality wine. They have developed rather rapidly and,

under the experimental storage conditions, have cleared very satisfactorily and in a minimum of time. Once mature they have kept only moderately well. The wines of region III have been very similar to those described above, but lower in acidity. This latter condition has influenced their balance and slightly reduced their general quality.

In the interior the Carignane is only fairly well suited for table wines. The products of region IV have been of only fair balance, medium or lower color, little flavor, low acidity, and average quality. They have suffered much from lack of freshness. They are here only bulk wines. In region V there is a further loss in quality; the wines are definitely flat.

The dessert wines from regions IV and V have been only ordinary to average, without the softness or mellowness expected in this type.

On the basis of its productivity and the average to lower quality, the Carignane is primarily suited only for bulk table wines. Even its best products have little character and will profit little from aging once they are stable.

Although some of the best Carignane wines have been produced in region I, the variety cannot be recommended there, primarily because of difficulty and expense in controlling mildew, but also because the crops would be light. In regions II and III it does well on the fertile soils of the valley floors. Even here the control of mildew will be difficult in cooler years and damp locations. It seems only wise to use the better locations and exposures of these districts for varieties more resistant to mildew and able to produce superior wines. It is, however, useful in the warmer and more fertile portions of region III.

Although its wines are not the best, Carignane is well adapted to the rich soils of region IV, where it comes into its own for large crops and sound common wines. In this region, if necessary, its grapes can be used for either table or dessert wine. It is poorly suited to region V.

*Gamay.*<sup>40</sup>—The Gamay is widely distributed in France. It is the principal variety of the Beaujolais region, and a lesser variety in Burgundy and other areas. There, it is moderately vigorous and productive. Quantitatively it surpasses the Pinot noir, but qualitatively it does not compare so favorably.

The clusters are of medium size, short-conical, compactly set with small-medium sized, short-oval berries. A thin skin makes the grapes susceptible to handling injuries and to raisining.

The fruit from regions I, II, III, and IV yielded a very well-balanced must for dry table wines. The acidity has been ample, and the pH much below the average. The color, however, is low, frequently only equaling that of a well-colored pink or *rosé* wine. The one lot from region V was rather over-mature. Its acid content was too low, its pH high, and its quality injured by raisining.

The wines from regions I and II have been distinct in aroma and flavor, well balanced, delicate, refreshing, and well finished. They were decidedly distinctive and above average in quality. They did not, however, possess the delicacy, richness, and finish of Pinot noir and Cabernet Sauvignon wines from the same areas. Even in these cool areas the color of Gamay is deficient for a well-colored normal red wine. Its lightness harmonizes well, however, with the other qualities—namely, liveliness, delicate flavor, and fruitiness.

<sup>40</sup> The variety referred to here is the Gamay Beaujolais. This is the principal variety of the Gamay group now grown in California.

The Gamay wines of regions III and IV were well balanced and well supplied with aroma and flavor, and have been less tart, although still light and refreshing. In cool years they have been pleasant and very acceptable, but in warm seasons they have tended to be heavy and flat—just common wine.

The product of region V was very ordinary. Since the variety is early, it ripens here in the intense heat of August, so that its acid content is low and raisining will be a difficult problem each year.

The Gamay is well adapted to regions I and II, where it will produce a light, delicate, refreshing wine above the average in quality. With particular care in timing the harvest, it may yield a very acceptable product in region III. The value of the wines is in their sprightliness, delicacy, and lightness. Unless provisions are available to preserve these, the variety should not be grown. It is not recommended for region IV or V.

*Grenache*.—The Grenache has been grown rather extensively in California. It is very vigorous and in most localities yields heavily. The vines cover their fruit well; in the cooler locations, in fact, heavy coverage with not-too-high resistance makes the variety more susceptible to mildew. It is rather resistant to the grape leafhopper, and in a measure to red spider.

The leaves are almost entire, yellow-green, and without hairs. The clusters are large, short pyramidal, with a very thick stem, and well filled to compact. The berries are small medium, round, and reddish-black. The juice yield is good.

Because of the very general distribution in California, samples were obtained from all regions—in many instances more than one sample from the same region.

After studying numerous lots of table wine produced from Grenache, it appears that the variety is not usually suitable for this type of wine. This was more strikingly true of the warmer regions; not one table wine of even ordinary quality was produced from these grapes in regions IV and V. The wines of III have been of average and above-average quality in only two out of six years. These wines have been lacking principally in acidity and character, have suffered from too much alcohol, and tended to become oxidized in flavor and color.

In the coolest regions the table wines of Grenache have not been consistently good. They have frequently been lacking in acidity, heavy, only mildly distinctive, and low in color. Hilgard,<sup>4</sup> noting the deficiency of color in Grenache, gave Carignane a better rank because of it. Nevertheless, the wines of region I for 1938, 1939, and 1940 and those of region II for 1937, 1938, and 1939 indicate real possibilities for pink or light-red wines. Further studies, with a more accurate timing of the harvest, should reveal locations where good to very good pink wines can be produced of this variety year after year.

The many lots of dessert wines from Grenache, have, on the whole, been very satisfactory. The Angelicas have been fruity, luscious, delicate, full-bodied, and rich, while the red sweet wines of the port type, have been fruity, distinctive, and well balanced, though somewhat lacking in color.

Judging from the analysis and observation on the Grenache, its possibilities for pink wine should be tested further in regions I and II, and it is certainly a

<sup>4</sup> See citation in footnote 16, p. 496.

good variety for Angelica, red sweet, and perhaps sherry. Its fruit will be well suited for these latter types in regions IV and V and the warmer parts of III. It is recommended for commercial planting only in these latter regions.

The present findings differ from Hilgard's: he states that Grenache cannot be recommended for any location yet tried, although he made wines of its grapes from Fresno, Tulare, Cupertino, and Livermore. Bioletti likewise failed to recommend it in 1907 and speaks of it as a common variety not to be planted in the coast counties. On the other hand, the present recommendations are supported by the uses to which Grenache is put in its home country, France. There the Tavel, the best known of all pink (*rosé*) wines, derives its character from the Grenache; and Banyuls, a rancio-flavored sweet wine of the south of France, is also a product of it.

*Mission.*—The Mission was the first grape of *Vitis vinifera* lineage planted in California.<sup>42</sup> In the beginning of wine production, dry wines were the primary product. It was, no doubt, the holdover impression from the poor dry wines of the Mission in early days and the limited tests of only five of his own that led Hilgard to state:<sup>43</sup> "There is little to be said in favor of our old, rejected friend, the Mission, except that it may still be useful in some localities as an ingredient of sherries. Its total lack of character and low acid render it unfit for any other purpose than blending where a neutral ingredient is desired."

Possibly Hilgard was unaware that the Mission variety has always been associated with the production of Angelica and that well before 1900 it had gained considerable reputation as the source of this wine. Lachman<sup>44</sup> attests to this as follows: "The Mission grape which was no doubt transplanted to this country by the padres, was found to adapt itself to our soil and climatic conditions. . . . The Angelica made from this grape has never been excelled by wine produced from any other variety . . . ."

The Mission grows vigorously and produces large crops. Its clusters are large, irregular-pyramidal in shape, loosely set with medium-sized, round, crisp, brownish-red berries.

The table wines produced have been almost complete failures, low in acidity and lacking in distinctiveness. They have been flat, lacking in flavor, deficient in color, and sometimes harsh. As regards these types, Hilgard's conclusions are correct—the variety should not be planted.

The possibilities of Mission for dessert wines, on the contrary, show promise for certain types. On the whole, its dessert wines have possessed average or better quality, though some have been difficult to keep. They have been smooth, full-bodied, delicately flavored, fruity, and fairly well balanced. Certain Angelicas have been luscious, mellow, golden, and very good. The dry sherries have been smooth, delicate, and pleasing.

Only one well-colored red dessert wine was obtained from the Mission—from grapes of Escondido in region IV. The other wines of this type have been pink to tawny. Aside from their deficiency in color, the red sweet wines had a mild but distinct aroma and flavor. Apparently they require special care to prevent oxidization and to retain as much acidity as possible.

<sup>42</sup> See citation for Leggett in footnote 6, p. 494.

<sup>43</sup> See citation in footnote 16, p. 496.

<sup>44</sup> Lachman, Henry. A monograph on the manufacture of wines in California. U. S. Dept. Agr., Bur. Chem. Bul. 72 (Pt. 2):25-40. 1903.

These observations upon the dessert wines of Mission not only confirm the earlier opinions regarding its value for Angelica, but also show its use for sherry and occasionally for red sweet wine. Its deficient color can be corrected by judicious blending without spoiling its soft mellowness.

The Mission is well adapted to regions IV, V, and possibly to III. In V its acidity may tend to be too low. It is recommended for dessert wines in these regions.

*Petite Sirah.*—The Petite Sirah is widely grown in California, and samples have been secured from every district. The grapes are highly susceptible to changes in climatic conditions. In the extremely warm year of 1936 the Petite Sirah was a complete failure in every district, the grapes raisining very early in the season and the resulting wines being alcoholic, flat, and coarse. In very cool seasons the heavily loaded vines in fertile soils of regions I and II will fail to ripen.

The Petite Sirah is a variety of good production and vigorous growth. When young its clusters are somewhat entangled in the canes, and considerable damage may be done them during harvest. It rots very quickly after early rains and, as indicated above, raisins easily in hot, sunny weather.

Usually, except in very hot years, the grapes can be harvested sufficiently early. (Region V samples were harvested in August.) The resulting wines, however, though of sufficient alcoholic content for table purposes, may be somewhat green tasting. If harvested later, the musts from this region are high in pH, and there is some difficulty in obtaining a clean fermentation. The experiments with dessert wine from Petite Sirah, though not extensive, sufficiently indicate that the variety is too high in tannin for this type of wine and accordingly makes a slow-maturing product. This is not a final objection to the use of the variety for this purpose, since some slow-maturing red dessert wines finally reach very good quality.

The adaptation of Petite Sirah in California indicates that it should be planted only in regions at least as cool as region III. Apparently it always matures its fruit under the coolest California conditions, unless overcropped, and its best table wines are regularly produced in these regions. The quality in region I has been uniformly above average, and a few samples have been outstanding.

These best wines are less aromatic than distinctively flavored varieties such as Cabernet Sauvignon, but they do have a characteristic aroma and flavor and, when properly vinified and matured, are recognizable. This flavor is not, however, typical of Burgundy wines of France, and the desirability of using Petite Sirah for making all Burgundy-type wines in this state is not yet indicated by commercial experiments.

In regions II and III standard red table wines have been produced in all but the hottest years, and the variety seems to have a permanent place as a heavy-bodied, red table wine.

The present recommendation is that no further plantings of Petite Sirah be made in regions IV and V; that plantings in III and usually in II be confined to those areas capable of, and to those producers who wish only to secure, an average-quality, heavy-bodied, red table wine. Plantings in region I should be restricted because the variety matures slowly, but may be made by those

willing to produce a moderately distinctive, above-average, slow-maturing red table wine.

*Pinot noir*.—The Pinot noir is the variety from which are made the Burgundy wines of France. It is widely planted in Europe, but only under the climatic and soil conditions of the Côte-d'Or have its red wines attained perfection.

The vines are somewhat below average in vigor. With long pruning they bear moderate crops. The clusters are small-medium, cylindrical, often winged, and well filled with small, short-oval berries. The skin is fairly thick, but not too resistant to water loss. The fruit matures very early.

The wines of Pinot noir from region I have been excellent in aroma and flavor, fruity, soft, very harmonious, superb in finish. They have revealed much of the true character of the variety when grown in a favorable environment. In short, they were among the outstanding quality wines produced in these investigations.

These wines fermented without difficulty and have aged normally but somewhat slowly. They have kept well. On the whole they were well colored.

The wines from regions IV and V were much commoner in quality. Although they possessed a fairly distinct aroma and flavor, they were unharmonious and often flat. Many were tainted with an overripe grape or raisin taste. They also aged more rapidly, tending to turn brown. Their poorer keeping quality was no doubt directly chargeable to the condition of the fruit at crushing and not to the variety. The color content was only approximately that of pink or *rosé* wines.

On the basis of these and past tests, the Pinot noir can be recommended for table wines in region I. With proper handling, vinification, and aging in this area the product will be of outstanding quality. The fruit is, however, very delicate, requiring unusual care in handling. The possibilities can be realized only by those willing to become specialists. The tendency of the young wines to become oxidized and flat requires that they be kept cool and out of the air as much as possible.

In the warmer regions (particularly in III, IV, and V) the Pinot noir will fail. Its fruit will ripen under the severe conditions of summer, long before most wineries are ready to operate. Under these conditions the mature fruit will be poorly balanced, and raisining will occur. The quality will be poor at best, and sound wines can ordinarily be produced only by blending.

*Refosco*.—The vines of the Refosco are vigorous, though not so strong as Carignane. It is a moderately productive variety. The fruit resists mildew but, as a result of the long internodes of the canes and the open character of the foliage, is subject to sunburn in the hot interior valleys. The vines produce well with spur pruning. During development of the vines the spurs should be left with more buds to compensate for their limited number and to spread the fruit.

The clusters are long and medium-large. The main stem of the cluster and its branches are strong, with berries firmly attached. The firm flesh is inclosed in a rather tender but thick skin. The combination of firm flesh, thick skin, and open-cluster structure has made the fruit fairly resistant to unfavorable weather conditions or light early rains. Ripening comes in late midseason.

The juice yield has been good. The fermentations have gone well and to completion, except when the fruit was much overripe. The wines from regions I and II were average in alcohol, with medium body, excellent color, pleasing aroma and bouquet, and sufficient acid. They were well supplied with tannin, but not enough to make them rough or to prolong unduly the aging period. In region IV the wines were somewhat heavier and fuller, but still balanced as regards their principal constituents. The wine from region V was very acceptable as a standard table wine. It may have benefited by the cool season of 1935, but Hilgard's and Bioletti's results support the very wide range of the adaptation. In all the regions, the table wine of Refosco surpassed Carignane in both balance and character.

The place for the Refosco, if grown in regions I to III, would be on the fertile flat soils. Here it will produce wines that are distinctive and well balanced. Although not great, they will be superior to Carignane, Mataro, and Mondeuse, and far better than Alicante Bouschet, Petit Bouschet, Grand noir, and similar varieties that now occupy much of this land. In region IV Refosco should interest those who wish to specialize in something well above average. Bioletti also recommended it for this region. It is not advised for region V as a table-wine variety.

*Salvador*.—*Salvador*, a hybrid of *Vitis Rupestris* and *Vitis vinifera*, is of interest because of its intense color. Its vines are of low to medium vigor, but very productive for their size. The clusters are small, slender, well filled with medium-small round berries. The pigment is present only in the skin, except in very ripe fruit, where there may be some diffusion into the pulp.

As shown by the figures of table 17 the *Salvador* musts and wines contain abundant acid and tremendous amounts of tannin and color. The American parent also gave this variety an aromatic flavor, somewhat objectionable in its wines.

The table wines of *Salvador* have been distinctly aromatic, heavy, rough, and intensely colored. With time they mellow down, though they remain too deeply colored.

With the addition of brandy, as in the production of dessert wines, the principal properties of these wines are diluted. They are, nevertheless, still very rich in tannin, the aromatic flavor, and color.

The primary, if not the only, merit of the wines is their blending value to correct deficiencies in color. For this they can be used in moderation without noticeably injuring the wines into which they are blended. If they are used too freely, the ill effects of the excessive acidity and of the aromatic flavor may more than offset the improvement in color. In general, a blend of 2 to 5 per cent should add sufficient color.

The *Salvador* has done well wherever it has been grown. Naturally, the color is more intense in the cool regions. In view of this fact, the relatively small amounts required, and the better success that can be had when the blender makes and understands his wines, it would appear only logical that this variety be grown only by the wineries utilizing it, regardless of their location. Since lack of color is seldom a problem in region I, II, and III, plantings there are not recommended. Vintners in regions IV and V who have difficulty in securing sufficient color for their red dessert wines might consider small

plantings of Salvador. A better procedure, however, would be gradually to plant larger acreages of varieties such as the Tinta Madeira, which are naturally well balanced in coloring matter.

*Tinta Madeira*.—This variety derives its name from two sources: Tinta from its color properties, and Madeira from the island. It is much more important in the Alto Douro Valley of Portugal, however, than in Madeira.

The vines are vigorous and somewhat more productive than those of Tinta amarella or Tinta Cao. To obtain full crops regularly, the vines should be pruned moderately long. The clusters are medium-sized, conical, shouldered, usually well filled. The berries are medium-sized, long-oval, black, with a thick but tender skin. Of the varieties of Portugal tested, the fruit of this and the Tinta Cao has regularly reached the crusher in the best condition.

The musts from region IV were poorly balanced for dry wines; the few table wines made of this variety were decidedly ordinary. Hilgard's observations, based on fruit collected from region II, agree with these findings.

At maturity the Tinta Madeira retains more acid than the other port varieties. This adds to its fullness of flavor. To date its wine has been the smoothest and best balanced of the red dessert wines produced in region IV.

The dessert wines have aged fairly rapidly. Though the young wines have been slightly astringent, this property has not retarded their mellowing; they have regularly developed a high degree of smoothness. The slightly higher acidity and moderate tannin content have improved the keeping quality.

This variety is not recommended for dry table wines. For red dessert wines it is among the best and is recommended for regions IV and V. It is a pity that a larger acreage has not been planted in the San Joaquin Valley. This is, however, a delicately flavored quality sort; and to bring its potentialities to full development it must be handled carefully. Rough handling and attempts at aging in very large tanks will almost surely result in disappointment. In region V care must be exercised in harvest to avoid raisining. In region III this variety may have some value, but further tests will be necessary.

*Trousseau*.—The Trousseau is grown extensively in the Jura region of France and, according to Olmo,<sup>4</sup> is the same as Bastardo, a prominent variety of the Alto Douro Valley, Portugal, where it is among the four varieties most extensively planted for the production of port.

The vines are vigorous and productive. The canes are semierect, with short internodes and many short laterals. This habit of growth gives the vines a leafy appearance and protects the fruit from sunburn. On the other hand, the dense coating of leaves favors mildew when sulfuring is neglected.

The clusters are medium-sized, almost cylindrical, usually winged, and compact. The berries are small, medium, oval, reddish-black, with a thick but tender skin. The variety matures early. When mature fruit is permitted to hang on the vines, raisining may set in promptly, especially on old vines.

For dry table wines the Trousseau has failed completely. This agrees with Hilgard,<sup>5</sup> who stated: "For a dry red wine . . . it is quite useless, lacking sufficient color, acid, or tannin." In addition these wines have been lifeless and very subject to deterioration during aging and storage.

<sup>4</sup> Olmo, H. P. *Le Trousseau et le Bastardo*. *Revue de Viticulture* 87:174-75. 1937.

<sup>5</sup> See citation in footnote 16, p. 496.

The low acidity, low tannin, and moderate sugar content of the musts make for mellow, soft, dessert wines. These properties, along with the somewhat spicy, fruity flavor, make up the character and high quality of such wines. These wines develop an oxidized taste very rapidly if the casks are not kept full.

The dessert wines are deficient in color. This, however, is characteristic of several other good port varieties as well. Most of the Trousseau dessert wines had a tawny color. Lack of color can be corrected by blending in a small percentage of some darker wine. Unfortunately the present large commercial demands are for the darker ports.

This variety cannot be recommended for dry table wines anywhere in our state, but can produce red dessert wines above the average in quality. Its limitations should be considered before planting. In region V and in the warmer part of region IV the fruit ripens very early, usually before the wineries are ready; hence it raisins and does not yield a quality product. In the coastal regions, where it ripens under cooler conditions, the fruit will be caught by rains in some years. The result will be the development of rot in the compact clusters.

Trousseau is adapted to regions III, IV, and V. Throughout these regions it will ripen before the usual autumn rains. With prompt harvesting and moderate care in handling, the crop will reach the crusher in sound condition. Even in these areas, Trousseau should be planted only by those able to give special care to its harvest, and perform extra work in bringing its wines to full development. It is a variety for the vintner who wishes to specialize—not for the mass producer. The Tinta Madeira and Tinta Cao will produce very good ports and do not have the viticultural handicaps of the Trousseau.

#### VARIETIES THAT CAN BE ONLY LIMITEDLY RECOMMENDED

Numerous varieties cannot be wholly recommended. The reasons differ from variety to variety. The most common reason is simply that other varieties excel them under most conditions for their particular type and quality of wine. Under particular conditions, some of these grapes have given good results in California and abroad. The mere fact that a variety can produce good wine does not, however, prove that others will not excel it if adequately tested. Furthermore, some varieties have succeeded under special, restricted conditions that can seldom be duplicated satisfactorily. This is true of certain varieties that have found a place in local and minor regions of European viticulture over a long period. The taste created for such varieties as Nebbiolo and Chenin blanc will insure their continued propagation. But to plant them here and expect their wines to compete with better ones is risky. Perhaps, as the California industry expands and greater attention is paid to particular flavors, some may find a local but permanent place.

Other varieties listed here have special qualities of production, possible dual utilization for wine and shipping, disease resistance, period of ripening, and the like. Where one or more of these factors must be specially considered, some variety in this group may prove useful.

Because of another factor, the present plantings, Zinfandel is included in this group. The Zinfandel has a permanent place in California for a distinc-

tive type of wine, but it is already the most extensively planted red-wine-grape variety, and only occasionally will its new plantings be as profitable as those of the varieties listed in previous sections. *All the varieties listed here have one or more defects, and one should plant them only after considering their handicaps.*

#### WHITE VARIETIES OF LIMITED RECOMMENDATION

Under this head are included blending varieties, Burger and Servant; varieties having a muscat flavor, Muscadelle and Muscat of Alexandria; table or natural sweet wine varieties, Aligote, Chenin blanc, Gray Riesling, Peverella, and Vernaccia Sarda; and dessert wine varieties, Inzolia and Verdelho. These have a wide range of climatic adaptation, some being suited to the cooler regions and others to the warmer. Table 18 gives the analyses of musts and wines of these varieties.

*Aligote*.—This variety is used for standard white wines in the Burgundy district of France. In California it appears to be capable of somewhat better results. Apparently no previous tests have been made.

The Aligote is of average vigor, productive, and ripens its fruit in midseason. The fruit is clean and reaches the crusher in good condition. The juice yield is average.

The musts were well above average in composition. Its wines have uniformly been clean and of average or higher quality. The flavor has been mildly rich and distinct, the color excellent, and the keeping good.

The Aligote will produce standard and better white wines in regions II and III. In I and in IV it will also produce average wine in most years. Under further testing more restricted areas may appear specially desirable. It should find a definite place in regions II and III.

*Burger*.—Burger is among the most extensively grown white wine varieties of California. The source of this variety is uncertain, but it is probably of rather minor importance abroad or its identity would have been determined.

The vines are of only moderate vigor, but will bear immense crops on fertile soils and good crops wherever grapes will grow. The vines are hardy and require spur pruning. They should be opened up as fast as possible in their development in order to separate the clusters.

The clusters are very large, irregular to conical-shouldered, generally very compact. The berries are of large-medium size, round, very juicy, waxy-yellow, without any particular flavor. The skin, easily broken, renders the fruit very susceptible to handling injuries in harvesting and to damage by early rains.

Except in region I the acid content has been only average, with many lots running low—this despite the relatively low to very low Balling degree of most lots. Although not a high-acid sort, Burger would probably possess a better balance, as regards sugar and acid, if not permitted to overbear. Often these vines are so heavily loaded that the fruit must be left on them for weeks after the normal time of harvesting in order to secure the minimum amount of sugar. Meanwhile the acid continues to decrease. This condition is most serious in the warmer regions, where the acid is normally lower and where it is depressed more rapidly because of the higher temperatures.

The wines from region I were very light in color and body, tart, and fruity,

(Text continued on page 571)

TABLE 18  
COMPOSITION OF MUSTS AND WINES OF WHITE VARIETIES WITH LIMITED RECOMMENDATION

Region	Number of samples	Average harvest date, and year	Must			Wine			Tasting record
			Balling degrees	Total acid, grains per 10 cc	pH	Alcohol, per cent	Fixed acid, grains per 100 cc	Extinct. tannin, grains per 100 cc	
Aligote									
I	1	Oct. 1, 1936	25.9	0.36	3.42	14.2	0.46	2.4	0.02
I	1	Oct. 5, 1937	21.6	0.68	3.01	11.0	0.62	2.1	0.03
IV	1	Sept. 3, 1940	22.2	0.44	3.62	12.0	0.38	2.4	0.03
IV	1	Sept. 13, 1941	22.4	0.76	3.41	12.3	0.65	2.6	0.07
Burger									
I	1	Oct. 26, 1935	19.3	0.05	-	8.9	0.03	2.0	0.04
II	2	Oct. 4, 1935	19.4	0.43	-	9.5	0.51	1.9	0.05
III	2	Oct. 6, 1935	18.8	0.49	-	8.7	0.52	1.0	0.05
IV	4	Oct. 19, 1935	17.9	0.46	-	8.3	0.38	1.9	0.03
V	1	Aug. 12, 1935	20.9	0.46	-	0.8	0.52	2.6	0.08
I	2	Oct. 7, 1936	20.1	0.65	3.19	10.7	0.04	2.2	0.03
II	3	Sept. 25, 1936	20.2	0.43	3.63	11.3	0.40	2.1	0.04
III	2	Sept. 22, 1936	21.4	0.57	3.34	12.1	0.55	2.5	0.03
IV	2	Sept. 21, 1936	18.3	0.37	3.99	9.7	0.35	2.5	0.03
V	1	Aug. 17, 1936	17.5	0.42	-	10.0	0.33	2.4	0.03
I	3	Oct. 18, 1937	17.9	0.75	3.15	10.3	0.42	1.8	0.04
II	5	Oct. 13, 1937	19.4	0.65	3.39	11.0	0.45	2.0	0.10
III	2	Oct. 5, 1937	18.5	0.63	3.37	10.9	0.56	2.3	0.03
IV	1	Oct. 2, 1937	17.8	0.65	-	9.5	0.43	1.8	0.01

\* For footnotes see end of table, page 570.

IV	1	Oct. 4, 1938	14.5	0.49	3.28	8.1	0.63	1.9	0.05	12
I	1	Oct. 18, 1939	16.8	1.14	2.76	9.7	0.63	1.8	0.3	25
II	1	Sept. 21, 1939	22.0	0.68	3.17	12.1	0.63	2.2	0.3	20
III	1	Sept. 10, 1939	18.7	0.90	2.05	8.9	0.66	2.4	0.4	17
IV	1	Sept. 19, 1939	23.4	0.71	3.60	10.6	0.64	2.6	0.2	25
I	2	Oct. 18, 1940	19.3	1.04	3.60	10.7	0.77	2.3	0.2	16
II	2	Sept. 22, 1940	18.7	0.82	3.11	10.5	0.65	2.1	0.2	8
III	1	Sept. 19, 1940	17.9	0.68	8.9	5.7	0.57	3.0	0.2	16
IV	2	Oct. 9, 1940	20.9	0.61	3.61	11.5	0.46	2.3	0.2	19
I	3	Oct. 6, 1941	18.0	1.10	2.96	10.4	0.86	2.2	0.6	4
II	1	Sept. 20, 1941	18.2	0.75	3.04	10.3	0.72	2.3	0.6	10
IV	1	Oct. 2, 1941	17.3	0.83	3.31	9.7	0.47	2.1	0.08	7
Fruity, some flavor. Duplicate lots as sparkling wine had good balance, but lacked flavor Very tart; little character										
Tart, very thin; grapes immature Light color, body, flat; common Exceedingly light color, not balanced, neutral Thin, neutral, possibly useful for blending Very light color, flat, neutral; common										
Chevlin blanc										
IV	1	Oct. 8, 1936	22.1	0.80	-	11.1	0.35	3.0	0.02	Average flavor and quality, but flat
I	1	Oct. 1, 1936	25.6	0.44	3.38	14.2	0.46	2.4	0.4	Pleasant, distinct flavor; average quality; flat
IV	1	Oct. 17, 1936	23.5	0.56	3.94	13.1	0.35	3.3	0.1	Very flat, tends to spoil
IV	1	Sept. 21, 1938	21.7	0.56	3.53	12.2	0.50	2.9	0.6	Rich body, some flavor, tends to spoil
IV	1	Aug. 31, 1939	24.0	0.61	3.45	10.8	0.54	4.3	0.2	Fairly neutral flavor; average quality natural sweet wine
IV	1	Sept. 19, 1940	23.5	0.64	3.52	10.4	0.35	7.5	0.1	Natural sweet type; well-balanced flavor
IV	1	Sept. 26, 1941	23.3	0.79	3.33	13.9	0.66	3.1	0.06	7
Rich body; above average quality										
Gray Riesling										
I	1	Oct. 26, 1935	20.2	0.78	-	11.9	0.34	2.3	0.02	Well balanced, heavy body, distinct flavor, flat
III	1	Sept. 29, 1935	23.7	0.39	-	12.2	0.43	1.8	0.2	Soft, distinct flavor, but not aromatic
I	1	Oct. 10, 1936	25.9	0.59	3.44	14.7	0.58	2.8	0.3	Slightly distinct; very soft; average quality
II	1	Sept. 30, 1936	26.1	0.42	4.06	15.3	0.39	2.8	0.3	Slight varietal flavor; flat, alcoholic
III	1	Sept. 22, 1936	23.4	0.51	3.80	12.6	0.38	2.4	0.3	Smooth, but flat, light, delicate flavor
IV	1	Sept. 2, 1936	26.1	0.27	3.04	14.5	0.28	2.7	0.3	Slightly distinct, rich flavor; flat, alcoholic
V	1	Aug. 20, 1936	24.1	0.41	4.05	13.3	0.30	3.0	0.03	Slightly distinct; heavy; alcoholic

(Continued on following page)

TABLE 18—(Continued)

Region	Number of samples	Average harvest date, and year	Must			Wine			Tasting record
			Balling degrees	Total solid content per 100 cc	pH	Alcohol, per cent	Fixed acid, grams per 100 cc	Extract, grams per 100 cc	
Ciray Reading (Continued)									
I	1	Oct. 17, 1937	22.9	0.67	3.52	12.6	0.37	1.9	0.03
II	1	Oct. 5, 1937	21.4	0.53	11.5	4.4	2.0	0.02	
III	2	Sept. 23, 1937	22.7	51	3.51	12.0	3.9	1.9	0.03
V	1	Aug. 27, 1937	25.5	53	3.80	14.1	5.5	1.8	0.03
III	1	Sept 25, 1938	25.4	38	3.55	15.2	4.2	2.2	0.05
V	2	Sept. 5, 1938	24.9	38	3.62	14.8	4.2	3.4	0.07
I	1	Oct. 1, 1938	22.1	72	3.15	12.3	5.6	1.7	0.04
V	1	Aug. 17, 1939	20.0	35	3.87	14.0	4.3	2.7	0.04
II	1	Sept 11, 1940	24.7	53	3.50	13.9	4.7	2.2	0.01
III	1	Sept. 4, 1940	25.7	44	3.55	20.9†	31	3.6	0.01
IV	1	Sept. 13, 1940	24.5	43	3.69	14.0	3.9	3.1	0.03
V	1	Aug. 7, 1940	24.5	48	3.55	18.9†	35	15.8	0.07
III	1	Sept. 6, 1941	24.8	6.52	3.29	13.5	0.05	2.5	0.07
Inzohu									
IV	1	Sept. 30, 1936	24.3	0.43	4.01	13.6	0.37	2.5	0.01
V	2	Aug. 13, 1936	21.9	40	10.8	2.7	3.0	0.04	
IV	1	Sept. 23, 1937	23.0	59	3.81	11.9	4.4	2.2	0.03
IV	1	Oct. 10, 1938	21.7	45	3.88	12.0	3.7	2.2	0.04
V	1	Aug. 31, 1938	21.4	49	3.77	11.6	3.6	2.2	0.06
IV	3	Oct. 13, 1939	26.3	41	3.79	21.4†	33	2.5	0.04
IV	1	Oct. 1, 1940	23.7	6.63	3.83	19.4†	0.31	6.3	0.06

Muscatelle										
IV	1	Sept. 19, 1935	25.0	0.86		13.7	0.42	2.7	0.06	
IV	2	Sept. 19, 1936	26.9	61	4.27	16.5	40	3.5	0.5	Distinct muscat, fair flavor; harsh
IV	4	Sept. 23, 1937	26.7	85	3.80	15.0	50	3.7	0.5	Distinct muscat; good flavor, harsh; alcoholic
IV	2	Sept. 28, 1938	28.0	75	3.81	15.3	48	3.1	0.8	Distinct muscat; flat, slightly harsh, ordinary
IV	3	Oct. 6, 1939	27.5	58	3.73	13.3	44	7.5	0.6	Distinct muscat; rich, full flavor, not balanced
IV	2	Oct. 31, 1940	30.2	.55	4.07	13.3	49	8.3	0.3	Mildly muscat, soft, rich; good natural sweet wine
IV	1	Sept. 13, 1941	20.0	0.59	3.19	21.1†	0.38	10.7	0.06	Distinct muscat although from unripe grapes

Muscat of Alexandria										
IV	10	Oct. 20, 1935	23.1	0.62		12.6	0.35	2.3	0.03	Fair aroma, harsh, flat, oxidized flavor
II	1	Oct. 5, 1936	24.9	35	3.73	18.6†	37	13.6	0.3	Distinct, fairly smooth; gray, medium quality
IV	5	Oct. 10, 1936	25.3	47	3.89	18.4†	39	12.7	0.3	Distinct, smooth, luscious; good quality
V	3	Aug. 22, 1936	25.0	47	4.15	18.3†	30	12.2	0.3	Fairly distinct; smooth; flat, ordinary
IV	3	Oct. 20, 1937	24.6	48	3.65	14.2	30	2.3	0.3	Slightly distinct; heavy, harsh, flat; poor
V	1	Oct. 12, 1937	23.0	36	3.68	17.9†	35	15.5	0.3	Slightly distinct; heavy, fair flavor, medium quality
IV	2	Oct. 17, 1938	20.7	43	3.53	12.7	39	1.9	0.5	Early distinct; not balanced, flat, ordinary
IV	1	Oct. 22, 1939	27.3	44	3.88	18.2†	33	10.1	0.3	Distinct aroma, fruity flavor, medium quality
V	1	Sept. 29, 1939	24.3	41	3.70	20.1†	28	11.3	0.1	Distinct aroma, fruity; flat; ordinary
II	1	Oct. 9, 1940	24.8	55	3.45	19.7†	36	14.5	0.3	Distinct aroma, fruity, rich, balanced; dessert wine
IV	6	Oct. 16, 1940	25.2	40	3.70	18.9†	25	13.5	0.2	Distinctive; fruity, balanced; good quality
V	1	Sept. 26, 1940	26.8	45	4.00	16.3†	29	14.6	0.3	Distinctive, slightly fruity, medium quality
IV	1	Oct. 7, 1941	27.4	0.57	3.60	14.8	0.34	3.0	0.07	Distinct muscat aroma, very flat, poor

(Continued on following page)

TABLE 18—(Continued)

Region	Number of samples	Average harvest date, and year	Must				Wine			
			Balling degrees	Total acid, grains per 100 cc	pH	Alcohol, per cent	Fixed acid, grains per 100 cc	Extract, grain, no extract, 100 cc	Tannin, no tannin, 100 cc	Color intensity*
Peverella										
IV	1	Sept. 23, 1935	23.0	0.51		11.8	0.52	2.2	0.03	Distinct flavor, balanced, soft, promising
IV	2	Sept. 24, 1936	26.3	0.58		13.1	0.48	3.0	0.03	Definite flavor, medium quality; lacks acid
IV	1	Sept. 13, 1937	24.2	0.47		13.8	0.47	2.5	0.03	Distinct flavor, like Chardonnay, soft, flat, good
III	2	Oct. 6, 1938	24.1	0.53		13.5	0.59	2.9	0.05	17
IV	1	Sept. 28, 1938	20.0	0.77	3.30	12.6	0.63	2.5	0.06	Distinctive, rich; grainy, heavy; good quality
IV	2	Sept. 11, 1939	22.4	0.77	3.11	11.6	0.60	2.1	0.04	Moderately distinct, soft flavor, balanced, good
IV	1	Sept. 4, 1940	22.1	0.90	3.50	11.6	0.64	2.5	0.02	Fruity, light; balanced, above medium quality
IV	2	Sept. 15, 1941	24.3	0.80	3.26	12.7	0.66	2.1	0.06	13
Red Traminer										
IV	1	Sept. 23, 1935	23.0	0.39		11.1	0.35	2.4	0.04	Exceedingly aromatic, but very flat
IV	1	Aug. 28, 1936	22.9	0.50	3.58	12.0	0.33	2.4	0.03	Very aromatic, but flat
IV	1	Sept. 30, 1937	23.8	0.37	3.92	12.1	0.36	2.3	0.02	Very aromatic, but flat and alcoholic
II	1	Oct. 4, 1938	21.0	0.39	3.27	11.7	0.52	1.9	0.04	25
IV	1	Sept. 14, 1938	23.6	0.43	3.49	13.3	0.37	2.3	0.06	36
IV	1	Aug. 16, 1939	23.1	0.74	3.20	12.1	0.59	2.5	0.03	40
IV	2	Aug. 23, 1940	22.1	0.73	3.49	12.6	0.41	2.2	0.03	11.9
IV	3	Sept. 9, 1941	23.0	0.79	3.49	12.1	0.50	2.7	0.06	27.6
										Aromatic, but flat, tendency to oxidize

Red Veltliner									
II	2	Oct.	1, 1935	24.0	0.58	11.6	0.39	2.3	0.04
I	1	Sept. 29, 1937	22.9	.59	3.61	12.6	.44	2.0	.04
III	1	Sept. 26, 1937	22.1	.53	3.83	12.0	.36	2.0	.02
I	1	Oct. 21, 1938	24.7	.52	3.60	14.0	.49	2.7	.05
II	2	Sept. 21, 1938	21.9	.49	3.45	13.2	.50	2.5	.04
I	2	Sept. 30, 1939	20.0	.60	3.19	10.3	.57	1.9	.03
II	1	Sept. 31, 1939	24.3	.51	3.88	12.6	.46	2.2	.02
IV	1	Aug. 16, 1939	19.0	.73	3.50	9.9	.39	2.3	.02
I	2	Sept. 27, 1940	20.3	.70	3.32	11.5	.52	2.7	.02
II	2	Sept. 16, 1940	22.0	.64	3.44	11.8	.54	2.5	.02
III	1	Sept. 4, 1940	24.2	.56	3.65	12.7	.48	2.6	.01
IV	1	Aug. 20, 1940	20.5	.71	3.23	10.7	.85	2.3	.02
I	1	Oct. 1, 1941	23.1	.67	3.20	13.9	.65	2.5	.07
II	2	Sept. 24, 1941	24.3	.70	3.30	13.2	.56	3.0	.05
III	1	Sept. 6, 1941	22.5	.073	3.18	11.7	.68	2.7	.04

Servant									
V	1	Sept. 11, 1935	22.5	0.45	..	11.3	0.51	2.3	0.03
I	1	Oct. 10, 1936	19.9	0.62	3.27	10.4	0.68	2.1	
II	1	Oct. 5, 1936	21.1	0.51	3.63	11.4	0.56	2.3	.02
IV	1	Sept. 25, 1936	20.8	0.47	3.62	11.0	0.41	2.2	.03
I	1	Oct. 24, 1937	18.0	0.95	3.10	10.7	0.65	1.9	.03
I	1	Oct. 18, 1939	18.0	0.94	2.90	9.9	0.90	1.6	.03
I	1	Oct. 18, 1940	17.9	1.30	3.02	8.9	0.92	2.5	.02
I	1	Oct. 10, 1941	18.6	1.27	2.95	10.1	1.01	2.4	0.03

(Concluded on following page)

TABLE 18--(Concluded)

Region	Number of samples	Average harvest date and year	Must			Wine					
			Balling degrees	Total solid grams per 100 cc	pH	Alcohol per cent	Fixed extract, grains per 100 cc	Tannin, grains per 100 cc	Color intensity*	Tasting record	
Verdelho											
IV	1	Sept. 23, 1936	23.5	0.58		10.9	0.39	2.3	0.04		Clean, flavorful, light table wine
IV	1	Sept. 17, 1936	24.6	.52	3.71	14.3	.33	2.9	.04		Distinct rich flavor, soft; heavy and flat
IV	1	Sept. 13, 1937	23.1	.92	3.53	12.2	.58	2.3	.02		Delicate, medium distinct, tart; good
IV	1	Oct. 10, 1938	24.0	.63	3.48	13.6	.61	2.4	.04	21	Fruity, distinct, balanced; good quality
IV	1	Aug. 12, 1939	24.2	.82	3.09	11.7	.56	2.1	.06		Clean; fruity, distinct, good quality
IV	2	Sept. 10, 1940	25.4	.67	3.54	12.8	.67	2.7	.03	15	Fruity, tart, balanced, above average
IV	1	Sept. 22, 1941	29.6	0.63	3.79	20.5†	0.43	14.8	0.04	14	Birch, fairly intense, balanced; Angelica. Duplicate lot produced a clean, well-balanced sherry
Verdicchio											
IV	2	Oct. 14, 1935	22.2	0.81		11.2	0.38	2.4	0.05		Pan aroma, flavor, smooth, average quality
IV	2	Oct. 1, 1936	26.1	.54	3.95	15.3	.47	3.2	.04		Full flavor, body, medium distinct, alcoholic
V	1	Aug. 9, 1936	20.6	.76	3.97	10.6	.33	3.0	.06		Pleasant flavor, fair balance; average
IV	1	Sept. 23, 1937	25.0	.66	3.22	14.2	.52	2.7	.06		Distinct aroma, fruity, full flavor, above average
V	1	Sept. 9, 1937	19.9	.75	3.58	10.5	.36	2.0	.04		Thin, little flavor or character, poor
IV	2	Oct. 6, 1938	21.2	.69	3.21	12.3	.64	2.6	.07	29	Fair flavor, slightly distinct, balanced, average
IV	4	Sept. 26, 1939	23.6	.74	3.06	11.8	.57	2.2	.03	19	Fruity, distinct, balanced, above average quality
V	1	Aug. 30, 1939	21.3	.67	3.43	10.4	.50	2.3	.03	12	Fairly distinct; fruity, little character
IV	1	Aug. 28, 1940	22.0	.72	3.16	12.2	.41	2.2	.03	10	Heavy flavor, slightly distinct, soft; flat
IV	1	Oct. 6, 1941	26.0	0.83	3.39	19.7†	0.40	0.9	0.04	30	Clean, sweet sherry of average quality

\*Determined in a color comparator using an arbitrary color standard made from Eastman ABC dyes, the color intensity increases as the figures increase.

†Fermentation arrested by the addition of grape brandy.

with some flavor. Although pleasant and refreshing, they had little substance or character. Sparkling wines produced from some of these lots by the bottle fermentation method, were fair to well balanced, but lacked flavor.

In region II the Burger reaches its best development year after year. The grapes mature every year and except in the occasional hot years possess a fair balance of sugar and acid. The wines were light, clean, tart, fruity, fairly well balanced, with some flavor and distinctiveness. They have matured early into palatable, refreshing wines of average quality. In the bottle they have developed a pleasing but slight bouquet.

In the cool years those of region III were pleasant and refreshing; but in warm years like 1936 they were flat and very ordinary. The lots from region III for 1939 and 1940 were too immature, because of overcropping, to produce balanced wines.

All the wines of regions IV and V were flat, lacked flavor, and tended to spoil.

The Burger has been considered to be preëminently a blending wine. The results support this finding within certain limits. Unblended, the wines lack flavor and character. In this form they can be considered only as neutral and thin though sometimes pleasant wines. Their neutrality or plainness, on the other hand, fits them for blending where the purpose is to reduce body, alcohol, flavor, and aroma. In warm years they have been used for equalizing the fermentation of high-sugar grapes. They can add little or nothing except lightness, the only property or component in which they have been outstanding. For use in blending the source should be limited to region II, and possibly III; the products of IV and V have proved unsuitable.

The Burger will not regularly mature in region I. Here it is also very subject to bunch rot in the years of early rainfall. In region II and in the cooler parts of III it will produce a light, pleasant, refreshing wine of ordinary character. These wines may, in addition, have considerable value for blending. The results in regions IV and V do not justify further plantings there. The use of these wines for blending is being overdone, to the detriment of some otherwise quite good wines.

*Chenin blanc*.—The Chenin blanc is the principal white variety of Anjou and Tourraine, France, where it produces dry and natural sweet table wines as well as sparkling (*mousseux*) wines. Although now found in several vineyards in California (often incorrectly as Pinot de la Loire and White Zinfandel), it was apparently not tested by either Hilgard or Bioletti.

The vines are vigorous and productive. The clusters are long, conical, winged, compact; the stem is very long and tough; the berries are medium-sized, oval, with tough skins. The fruit resists handling injuries and rot except in humid regions where, when overcropped, it develops considerable bunch rot. It is crushed without difficulty, and the juice yield is good.

At Davis it has produced table wines of slight flavor, full body, medium-to-low acidity, and average quality. These wines have tended to be heavy and lacking in freshness.

The table wine from region I was pleasant, distinctly flavored, heavy but not badly balanced, and good in quality. Even for this region it lacked in acidity; but 1936 was a season favoring low acid.

To date, the natural sweet wine has been the better product. It was well balanced in its several components, though not particularly distinctive. This better showing as a natural sweet wine is not surprising, since the product in France more often than not retains a quantity of sugar. The wines of this type are not equal, however, to those of the Semillon, at least in the districts in which it is now grown.

On the basis of the results to date, it appears that Chenin blanc will, in the proper environment, produce standard table wines and that its quality is relatively the same here as abroad. It cannot compare with the quality, character, and finish of Pinot blanc, Chardonnay, and Semillon.

The variety may, because of its productivity, find a place on the fertile valley soils of regions II and III. In the cooler years and with early rainfall it will suffer from excessive bunch rot. It has no place in regions IV and V.

*Gray Riesling*.—It is most unfortunate that this variety has become established in California under this name, for it possesses none of the genuine aromatic qualities of the true Riesling. It has a mildly spicy flavor, but nothing more.

Gray Riesling is a strong, vigorous grower. During the development years it should be pruned long to insure full crops. Once the vines are well established, long spurs may suffice. The clusters are small, conical, shouldered, compact; the berries medium-sized, oval, and greenish-pink to brown. Since the fruit is very firm and difficult to crush, the juice yield is small.

The variety is rather susceptible to mildew, but otherwise reaches the winery in good condition except when early rain causes rot.

The table wines from regions I, II, and III were slightly distinct in aroma and flavor, soft, fairly well to well balanced, ordinary to good in quality. None of them reveal possibilities of anything more than sound, clean table wines. Their primary weakness was a deficiency in acid.

The table wines from regions IV and V were full-bodied and lifeless. Even though more timely harvesting would have improved them, they would still have remained unbalanced and flat.

Dessert wines of the Gray Riesling have shown promise for both sherry and Angelica. In these types the balance has been good, and the softness and mildly spicy flavor are desirable.

The results indicate that the Gray Riesling can produce clean, standard table wines on the more fertile soils of regions I and II and the cooler parts of region III; but at present no plantings are recommended. The wine is too soft and undistinguished to compete with the better varieties. It should not be planted for table-wine production in regions IV and V. Here it produces good to very good dessert wines, but its production may be a limiting factor. Since other varieties are already known to be useful, it is not recommended. Should a demand for a "natural" white port develop, plantings in regions IV and V should be considered.

*Inzolia*.—The Inzolia is not suitable for dry table wine, being very low in acid at even a moderate sugar content. Because it ripens slowly, not attaining high sugar except late in the season under the best conditions, it is likewise not suitable for Angelica and therefore seems useful only for sherry material.

The grapes reach the winery in very good condition even after early fall

rains. Their texture is very firm, crushing is somewhat difficult, and the juice yield is low. All the table wines produced between 1936 and 1938 were flat and lacking in character, and in some cases showed deterioration shortly after they were prepared. The sherry material and sherries made during 1938 to 1940 were, on the contrary, well balanced, and acquired good sherry character after moderate baking.

The variety could be recommended only for regions IV and V. Until, however, further tests demonstrate a higher quality in the sherries, Inzolia is not recommended even there, since Palomino is available. If plantings of any other variety are contemplated for sherry production, the Inzolia is suggested.

*Muscadelle*.—The vines of the Muscadelle are vigorous, with slender semi-upright canes. Production has in some instances been disappointing, apparently because of improper pruning rather than variety, and usually only with young vines of limited development. At Davis five-year-old vines that were spur-pruned produced only 18 pounds apiece, whereas cane-pruned vines produced 27 pounds. Two years later the production under the same pruning treatments was 25.7 and 27.3 respectively. There has been no difference since. As is shown by the vine growth, as well as by the composition of the fruit, the retention of some canes during the first six or seven years has been highly beneficial. The variety is moderately resistant to mildew. Since it leafs out late as compared with many varieties, it may escape spring frosts in some locations.

Since the clusters are small, 3 to 6 inches long, loose and slender, harvesting costs are somewhat above the average. The skin is thick and tough, and the berries are very firmly attached to the pedicels. These qualities greatly increase the resistance to rot and mechanical injuries: the fruit can be left on the vines until very ripe, and the large amount of foliage prevents sunburn or raisining. The pulp is soft and yields only a moderate amount of juice. The free-run juice is very thick, and clarification of the must is therefore difficult.

The dry wines from region IV have been very rich in the muscat component, but usually heavy, alcoholic, and not too well balanced. In general they have been harsh, lacking in life, and poorly finished. The natural sweet wines have been much better balanced for the type and seem to indicate the place for the variety. In these the sugar appears to mask the harshness, and the other components become quite harmonious. Even so the wines do not equal those of Muscat Canelli or Orange Muscat.

In region III the variety may have a limited place for blending in the production of natural sweet wines. Here and in region II it may resist unfavorable spring and fall weather conditions somewhat better than the other muscat varieties. Elsewhere other varieties of more pronounced aroma, better general balance, lower harvesting costs, or greater productivity will be preferable.

*Muscat of Alexandria*.—Only of late has the Muscat of Alexandria been used on a large scale as a wine grape in California, although occasionally used in Spain for wine. It is preëminently a raisin grape and, as such, has made a place for itself both here and abroad, particularly in the Malaga district of Spain.

The clusters are long and loosely set with large berries of nonuniform size, usually obovoid. The fruit ripens in mideason unless the vines are overcropped. As the foliage is not dense, much sunburning or raisining may occur

if the fruit is left on the vines too long. The proper period for harvesting depends on the size of the crop and the amount of the second crop. Much undue raisining is permitted to occur because the grower harvests the light-cropped vines at the same time as the very heavily laden vines, which may contain much second crop. To be sure, the muscat flavor does not adequately develop until the grapes are yellow. On the other hand, the flavor of wines from overripe, raisined grapes is flat and raisiny, while the color is too dark. The ideal picking arrangement would be to separate the green from the ripe fruit at picking time and to use the green grapes for grape brandy to be used in arresting the fermentation of muscatel wines.

The dry table wines from Muscat of Alexandria have been a failure—harsh, poorly balanced, flat, and only poor to ordinary. Although the young wines have had a pronounced aroma, this has been practically lost by the time they were mature. The variety does not contain sufficient acid for dry wines, and its characteristic harshness is unleashed in this type. By adding large amounts of acid and fermenting at low temperatures one can produce a palatable dry muscat wine. Even so, the wines lack in fruitiness and are rather coarse.

Dessert wines have been more promising—fairly smooth, well balanced, fruity, and good in quality. The characteristic varietal harshness is usually sufficiently covered by the sugar in this type to pass unnoticed. The flavor, however, is not the best. Hilgard<sup>47</sup> wrote, "Though the Muscat flavor is in such high repute for 'vins de liqueur' in Europe, it seems somewhat discredited in California. This is doubtless due to the use of the Muscat of Alexandria, which is much inferior to the Muscatel [*sic* Muscat Canelli] for this purpose." In the dessert wines the muscat aroma is preserved much better, so that the well-made wines are rich in this property at full maturity.

Generally, the dessert wines from Muscat of Alexandria have not equalled those from Muscat Canelli or Malvasia bianca.

Muscat of Alexandria is well adapted for producing raisin and table grapes and bulk dessert or muscatel wines in the San Joaquin Valley (region V). In the southern California areas of region IV this variety attains its highest quality, particularly around Escondido. Except for the latter location, in which other varieties have not been tested, its dessert wines are surpassed by those of Muscat Canelli and Orange Muscat. Where facilities are available and where the very best muscatels are desired, these other varieties should be preferred to it. The post-Prohibition demand for cheap muscatel wine may be only transitory. At any rate, the wisdom of producing large quantities of very sweet, easily recognizable, aromatic wine from muscat grapes is questionable. Judging from the enological experience of Italy and France, there is a place for high-quality muscat-flavored dessert wines. These can be better produced by using the better muscat varieties mentioned above.

Muscat of Alexandria is a moderate grower on rich soils, but is not successful on very sandy soils. Its production is governed by its vigor. It is somewhat more productive than Muscat Canelli on the same soils, but it has been equalled in production by Orange Muscat wherever the two have been compared.

*Peverella*.—Peverella is a variety of the southern Tyrol. Its value was not recognized by Hilgard, who obtained only ordinary wine from it. Bioletti,

<sup>47</sup> See citation in footnote 16, p. 496.

however, recommended it for the coast counties, and he also found it to produce standard wines under warmer conditions.

Its clusters are large, conical, and closely set with medium-large, firm, short-oval berries. The fruit matures in good condition. The berries are easily crushed, and the juice yield is slightly above average. On fertile soils the vines are vigorous and productive.

Most samples of must from region IV have had a good acid content; none have been very high, but neither have those of low acidity been very low. As a result the wines have been fairly well to well balanced. They have been distinct in flavor, fruity, soft, rich, full-bodied, and medium to good in quality.

The Peverella should be a good variety for the cooler parts of region IV and perhaps will reach its best quality in III. Here it will have sufficient acid in most years and will ripen its fruit. In region V it will be just another variety because of insufficient acidity, while in I and possibly II the fruit may fail to mature. Peverella is recommendable for planting in region III and probably IV for standard white table wines.

*Red Traminer*.—This variety is well known but of limited importance in Europe, where it is frequently called the Gewürz Traminer. It has small, nearly entire leaves. The clusters are likewise small. The berries, almost round, are closely set in the clusters. The skin is rather thick and russet or pink late in the season. The grapes ripen early and in region IV will raisin if left on the vines too long after maturity; but they reach the crusher in good condition because the skin is so thick. The juice yield is below average. Unless the fruit is pressed immediately after crushing, the musts and wines will have too much color.

In region IV, if left until September, the fruit becomes too low in acidity. Even in August the pH is too high for the best table wines. Unfortunately it has not been tested sufficiently under the cooler conditions of regions I, II, and III to predict accurately its performance. Hilgard tested it in several locations in the Santa Clara Valley, probably in region II. He reported very low acidity, but this was probably because of lateness in harvesting his samples.

Although very low in acidity and a poor producer, Red Traminer was recommended for the coastal counties by Bioletti in 1907. The reason is obvious. The grapes and wines have a very distinctive aromatic flavor even in region IV. Every sample produced has been aromatic. This almost muscat type of flavor has brought the variety into general use in Alsace in France. The flavor is not associated with a harsh, bitter after-taste, as in the usual dry muscat. Although it can definitely be stated that the Red Traminer should not be planted in regions III, IV, and V, a final report for regions I and II cannot now be made. Comparing the available data, however, it is recommended for trial plantings only in the cooler parts of region I.

*Red Veltliner*.—This late-ripening variety produces well. The clusters are large and winged. The berries, small and oval, are closely set. Lateness of ripening and compactness of cluster may result in some rot during early rainfall. The juice yield is average.

This variety is planted in several locations in regions I, II, and III. The musts have had only an average amount of acid even when the harvest was too early. The best wines came from region I, especially San Benito County. Re-

gions II and III produced wines variable in quality, but not consistently distinctive in flavor. Only two wines were produced from region IV. Of these, one was flat and heavy; the other of good acidity, but only ordinary flavor.

Hilgard tested a Green Veltliner, which he did not recommend. Bioletti, though familiar with the variety, failed to mention it. Not a single outstanding wine has been produced from it, though some were very sound, clean, and palatable. Red Veltliner is recommended for standard wines in region II.

*Servant*.—Because of its large berries the Servant has generally been considered a table grape. It is a vigorous grower and prolific bearer wherever it has been planted. The very large clusters are well filled with thick-skinned berries. The fruit withstands unfavorable weather conditions very well, better than practically any other variety.

In regions IV and V the Servant matures with a Balling-acid ratio adapting it for table use; but there it is poorly suited for table wines, being far too low in acid at 20° Balling. Besides, its wine is deficient in flavor.

In the north coastal areas, on the contrary, its Balling-acid ratio adapts it for dry table wines. Here it produces a light, pleasant wine, but with little aroma or flavor. The musts are easily fermented, and the wine matures rapidly. It is too light to keep for a long time, but for blending with heavy-bodied alcoholic wines is equal to Burger. Several tests using wines of this variety from region I as a part or all of a sparkling wine base have given clean-tasting, neutral wines. Folle blanche from the same district, however, gave more flavorful wines for this purpose, as did other varieties as well.

The Servant can never be considered as producing more than a blending wine. Its products in region I and II will possess more acid at the same alcohol content than those of Burger, but neither variety has sufficient alcohol. Its fruit, too, is not so subject to rot as Burger. Under a few cool conditions of region I, therefore, it may replace the latter for blending wines.

It cannot be recommended for the production of Servant wines as such.

*Verdelho*.—The Verdelho is cultivated extensively on the island of Madeira. In California it has been planted very little. Its vines are above average in vigor. If clusters alone counted, it would be very productive; but the clusters are small. Longer pruning will increase the yields. The clusters are short to medium, conical, usually with one or more shoulders. The berries are small, long oval, their light green becoming yellowish at maturity. This variety matures its fruit early. The firm berries and loose clusters make the fruit resistant to bad weather.

Its dry wines from region IV have possessed a pleasing, rich, fruity aroma and flavor and have been sufficiently well balanced and finished to indicate merit. The wine of the hot season of 1936 was heavy and too low in acidity. The variety should be tested further, especially in region IV, for sherry. The present results with Angelica and sherry have been very promising and appear to agree closely with the earlier findings of this station. Hilgard stated:<sup>48</sup> "It acquires a marked and delicate 'rancio' very quickly and easily, and its full aroma and high quality make it very valuable as an addition in the making of sweet wines." Its fruit ripens regularly without undue raisining—a valuable characteristic in a dessert-wine grape.

<sup>48</sup> Full citation given in footnote 16, p. 496.

The Verdelho will add quality to the white dessert wines of region IV. As elsewhere, however, the cost of harvesting the small clusters must be considered. For this reason and because of its low production, its place here is questionable. It may find its best use for blending purposes to add quality to thin sherries and Angelicas.

Because of its earliness, Verdelho is not so well adapted to region V as to region IV.

*Vernaccia Sarda.*—The Vernaccia Sarda is a vigorous grower and heavy producer. Its clusters are large, long-conical, shouldered, well filled to compact; the berries are medium-sized, round, and very dark green, with a medium-thick, tough skin. It matures in late midseason.

At normal maturity the fruit in region IV yielded a must of moderately suitable balance for dry table wines. The neutral character of this grape makes its wines, as might be expected, only average. They were mildly distinct, fruity, and full-bodied, typical of the standard table wines produced under such conditions.

Even the must of fruit grown in region V retained a fair acidity. The dry wines, however, were of somewhat poorer balance than in region IV. Their flavor was less pleasing, and they lacked finish. All these wines displayed a tendency to oxidize, ullage requiring special attention in their development.

To date, the sherries have been only average. Although well rounded and full-bodied as dry wines, the sherries have not been too harmonious. With further aging they may show improvement.

In region IV the Vernaccia Sarda produces a table wine of about average quality. There it will merit consideration only for bulk wines. Because of a higher degree of acidity and a mildly distinct aroma and flavor it will, under most conditions, produce better white table wines than Green Hungarian, Palomino, or Burger.

Although not particularly well adapted to region V, Vernaccia produced some fair dry white table wines. Its use here should depend on the demand for common bulk dry white wines. In general it offers most promise as a blend in the production of sherry. It is not now recommended for planting in California.

#### RED VARIETIES OF LIMITED RECOMMENDATION

Most of the varieties listed here are suitable for red table wines in one or more regions. All have, however, one or more defects which limit their usefulness. These include Aramon, Beclan, Bolgnino, Charbono, Fresia, Grignolino, Gros Manzenc, Lagrain, Mammolo Toscano, Meunier, Mondeuse, Nebbiolo, Negrara Gattinara, Raboso Piave, Saint Macaire, Sangioveto, Tannat, Valdepeñas, and Zinfandel.

Also listed is a variety that produces blending wine, Alicante Ganzin; two dessert-wine varieties, Black Malvoisie and Tinta Cao; and a muscat-flavored variety, Muscat Hamburg. The analyses of musts and wines of these varieties for various regions are given in table 19.

*Alicante Ganzin.*—The Alicante Ganzin is a hybrid of the Alicante Bousschet and Aramon × Rupestris Ganzin. This indicates some American blood and the source of the abundant color; its juice is intensely red at maturity. The cross has also endowed the variety with some resistance to mildew. Its

(Text continued on page 592)

TABLE 19  
COMPOSITION OF MUSTS AND WINES OF RED VARIETIES WITH LIMITED RECOMMENDATION

Region	Number of samples	Average harvest date, and year	Must			Wine			Tasting record
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol per cent	Fixed acid, grams per 100 cc	Tannin, grams per 100 cc	
Alicante Ganzan									
V	1	Sept. 11, 1936	21.1	0.76	9.9	0.52	3.5	0.32	V-100
V	2	Aug. 30, 1936	20.7	.52	3.63	11.9	.52	3.5	3VR-23
V		Oct. 12, 1937	22.4	.84	3.60	18.1†	.41	12.8	24
IV	1	Oct. 10, 1936	21.5	.70	3.48	12.6	.61	3.2	3VR-35
IV	1	Sept. 25, 1939	24.5	.72	3.32	21.7†	.58	12.2	31
IV	1	Oct. 15, 1940	26.2	.71	3.80	20.4†	.38	11.3	-
IV	1	Oct. 22, 1941	26.4	0.97	3.31	16.6†	0.62	10.1	0.40
Aramon									
I	2	Oct. 20, 1936	18.3	0.59	-	8.7	0.55	2.3	0.11
II	1	Oct. 9, 1935	17.9	.64	-	9.6	.48	2.2	0.08
III	1	Oct. 7, 1935	19.5	.50	-	10.4	.40	2.2	3RY-5 2R-6
I	2	Oct. 16, 1936	18.1	.57	3.48	9.9	.43	2.3	13
III	1	Sept. 25, 1936	19.6	.43	3.70	10.3	.36	2.7	Ry-4
I	2	Oct. 16, 1937	20.5	.84	3.22	10.5	.63	2.2	13
III	1	Oct. 8, 1937	18.2	.63	3.38	9.5	.56	2.1	15
I	2	Oct. 19, 1938	18.4	0.71	3.26	10.5	0.64	2.4	1VR-20
								0.18	118

\* For footnotes to table see page 591.

I	2	Sept. 26, 1939	19.2	0.77	3.01	10.7	0.69	2.1	0.11	3R-12	123
II	2	Sept. 23, 1939	18.7	0.72	3.01	10.2	.68	2.0	13	63	
IV	1	Sept. 19, 1939	21.8	0.79	3.28	10.6	.55	2.3	.07	20	
I	1	Sept. 22, 1940	16.7	1.06	3.10	10.0	.66	2.6	13	163	Very tart, sharp, medium-red color; blending type
II	1	Sept. 14, 1940	18.6	0.96	3.40	9.5	.53	2.3	12	74	Fruity, poor color; thin; common
III	1	Sept. 25, 1940	21.3	0.66	3.42	11.6	.62	2.5	.16	118	Light body; medium color; little character
IV	2	Sept. 24, 1940	20.9	0.78	3.40	10.7	.39	2.6	.13	52	Thin, very light color, lacks character
I	1	Sept. 28, 1941	18.8	0.97	3.02	9.8	.66	2.4	18	166	Thin; early-maturing, fruity; palatable
IV	1	Oct. 2, 1941	21.3	0.86	3.22	11.8	.52	2.4	0.12	19	Slightly flat, pleasant; early-maturing
Bechan											
IV	1	Sept. 23, 1935	20.0	0.40	...	9.9	0.36	2.3	0.09	5VR-13	
Vt	1	Sept. 6, 1935	22.2	.57	...	9.1	.30	2.7	14	5VRy-11	
I	1	Sept. 30, 1936	25.3	.53	3.47	13.9	.52	3.2	23	R-53	
IV	1	Aug. 23, 1936	20.2	.62	3.70	10.1	.39	2.3	10	3R-6	
Vt	1	Aug. 17, 1936	24.0	.65	...	13.6†	.40	11.3	.09	3R-12	
III	1	Oct. 19, 1937	21.5	.58	3.35	12.9	.60	2.8	16	3VR-27	
Vt	1	Sept. 24, 1937	23.2	.48	3.90	11.8	.49	2.9	16	R-10	
III	1	Oct. 4, 1938	17.2	.46	3.05	10.1	.	2.2	.09	3VR-15	
IV	1	Sept. 21, 1938	20.2	.41	3.41	.	.	2.8	10		
II	1	Sept. 29, 1939	25.0	.67	3.12	13.8	.68	3.2	.07	.	
III	1	Sept. 22, 1939	21.5	.71	2.98	11.1	.71	2.2	.08	290	Fruity, full body, color, some character
IV	1	Sept. 6, 1939	22.7	.53	3.30	11.4	.60	2.6	11	222	Fruity and tart, medium body, character
IV	2	Aug. 29, 1940	21.0	.66	3.41	10.0	.36	2.3	.04	78	Oxidized and flat; poor quality
V	1	Aug. 16, 1940	21.2	.41	3.30	11.4	.63	2.7	11	166	Unbalanced, little character
IV	1	Sept. 29, 1941	22.7	0.63	3.44	12.0	0.43	2.7	0.12	134	Medium distinctive, balanced, except for low acid

(Continued on following page)

TABLE 19—(Continued)

Region	Number of samples	Average harvest date, and year	Must			Wine			Tasting record
			Balling total acids, degrees	pH	Alcohol, per cent	Fixed acid, grains per 100 cc	Extract, Tanin, grains per 100 cc	Color intensity*	
Black Malvoisie									
I	1	Oct. 10, 1935	19.7	0.35	10.3	0.53	2.5	0.12	5VR-10
III	2	Oct. 5, 1935	21.6	4.6	11.6	.43	2.3	.09	5VR-9
IV	3	Oct. 1, 1935	21.6	5.7	13.5	.41	2.4	13	3VR-11
V	3	Sept. 4, 1935	25.3	5.5	11.7	.35	2.9	11	3Vly-11
III	2	Oct. 2, 1936	24.2	3.5	3.79	12.9	37	2.7	15
IV	2	Sept. 16, 1936	22.9	5.1	3.67	16.3†	40	8.5	VR-13
V	2	Aug. 25, 1936	21.5	4.1	3.85	15.5†	31	8.9	3R-8
III	2	Oct. 9, 1937	23.5	5.4	3.46	17.3†	42	5.3	08
IV	1	Oct. 2, 1937	23.2	6.2	4.12	16.8†	43	5.2	3R-5
V	1	Oct. 12, 1937	27.3	4.4	3.74	20.3†	30	13.0	R-8
IV	1	Sept. 21, 1938	25.4	4.4	3.78	13.9	3.2	1.8	R-15
V	1	Oct. 3, 1938	25.4	2.9	3.86	18.7†	25	11.6	2R-10
I	1	Oct. 1, 1939	20.0	5.6	3.19	11.2	5.6	2.2	14
III	1	Oct. 1, 1939	19.0	6.3	3.26	10.1	3.9	2.1	07
IV	1	Oct. 3, 1939	23.2	5.2	3.60	19.3†	3.8	12.6	03
IV	1	Oct. 1, 1940	28.0	5.2	3.90	19.8†	42	12.0	07
V	1	Aug. 29, 1940	24.8	6.5	3.72	17.5†	47	11.0	13
IV	1	Oct. 29, 1941	24.0	0.54	3.51	10.1†	0.37	13.6	0.06

Bulgino											
IV	2	Sept 28, 1935	22.0	0.90	10.0	0.49	2.6	0.12	3YR-23		Ordinary flavor, picked too early
IV	3	Sept. 28, 1936	25.5	.68	3.45	13.1	53	3.1	14	3R-25	Ordinary; some flavor, grapes overripe
IV	3	Sept. 29, 1937	24.3	.75	3.44	12.5	50	2.5	.16	3YR-25	Fruity flavor; average quality
IV	2	Oct. 4, 1938	21.6	.79	3.21	11.3	62	2.8	13	2R-11	Balanced; fairly tart, average quality
IV	2	Sept. 9, 1939	23.9	.89	3.20	11.8	75	2.7	10		Tart, high acidity; slightly astringent; fruity
IV	2	Sept. 7, 1940	21.9	.99	3.30	10.7	68	2.7	.14		Slightly above average quality; fruity
IV	3	Sept 22, 1941	23.4	0.97	3.09	12.6	66	2.8	0.15		Tart; fruity, medium distinct flavor, balanced
Charbono											
I	2	Oct. 22, 1935	19.5	0.65	..	9.7	0.63	2.6	0.12	3YR-34	Good color; above average quality, flavor
IV	2	Oct. 9, 1935	18.9	.63	4.06	8.9	45	2.3	.09	VR-6	Poor quality, little flavor, too thin
I	4	Oct. 1, 1936	20.0	.49	4.01	10.7	49	2.9	17	VR-14	Balanced, medium distinct flavor; standard wine
II	2	Oct. 4, 1936	21.9	.37	4.01	11.6	49	3.1	17	3YR-25	Flat; average flavor and quality
III	1	Oct. 9, 1936	24.4	.35	4.06	13.0	54	3.8	15	4YR-42	Oxidized; poor color and flavor; harsh
I	2	Oct. 20, 1937	19.3	.72	3.31	9.9	60	2.3	15	4YR-22	Slightly distinct, good balance, full color
II	1	Sept. 22, 1937	22.1	.52	3.54	11.1	56	2.9	15	3YR-32	Distinct flavor, soft, above average quality. A duplicate lot as sparkling wine also above average quality
IV	1	Sept. 23, 1937	21.0	.54	3.68	10.5	48	2.4	11	4YR-19	Slightly oxidized; lacks character and flavor
I	1	Oct. 22, 1938	20.1	.31	3.17	11.2	54	2.4	18	3YR-36	Balanced, simple flavor; average quality
IV	1	Oct. 10, 1938	19.0	.49	3.62	10.5	63	2.6	.09	5YR-14	Slightly fruity; ordinary flavor
I	2	Oct. 7, 1939	20.5	.69	3.25	11.3	.64	3.1	23		Full body; slightly distinct flavor
II	2	Sept. 27, 1939	21.2	.51	3.37	11.5	.55	2.7	11		Full body; good color, fruity; pleasant
III	1	Sept. 22, 1939	20.9	.63	3.03	11.1	.75	2.5	23		Good aroma and flavor; medium distinct
IV	2	Sept. 17, 1939	21.4	.67	3.33	10.9	.45	2.4	.06		Balanced, but flat; average quality
I	2	Oct. 11, 1940	22.0	.89	3.20	11.1	.56	2.7	12		Fruity, medium character, above average quality
IV	2	Oct. 11, 1940	23.7	.47	3.81	17.11	36	10.7	0.9		Average quality; common flavor
I	1	Oct. 10, 1941	19.4	.92	3.16	9.9	.74	2.8	16		Very tart; good color; useful for blending
IV	1	Oct. 13, 1941	21.3	0.57	3.62	11.0	0.41	3.2	0.15		Flat; very poor, good color

(Continued on following page)

TABLE 19—(Continued)

Region	Number of samples	Average harvest date, and year	Must			Wine				
			Total acid, grams per 100 cc	pH	Alcohol, per cent	Fixed acid, grams per 100 cc	Extract, grams per 100 cc	Tannin, grams per 100 cc	Color intensity*	Tasting record
Fresa										
V	1	Aug. 23, 1935	22.1	0.75	10.3	0.60	2.9	0.29	R-28	Distinct; pleasant aroma, fruity, tannic
V	1	Aug. 17, 1936	20.3	0.72	3.62	9.8	.46	2.8	2R-11	Astringent, distinct, typical flavor
V	1	Sept. 9, 1937	20.8	0.64	3.53	11.3	.58	2.7	R-15	Distinct, pleasant aroma, astrigent
IV	2	Sept. 30, 1938	21.8	0.68	3.54	12.3	.63	3.3	3VR-15	Fruity, typically distinct flavor, tannic
V	1	Aug. 31, 1938	22.0	0.69	3.34	13.4	.69	3.3	27	Distinct aroma; slightly rough; fruity; balanced
IV	1	Aug. 31, 1939	23.7	0.63	3.15	11.0	.66	3.0	16	Flavorful, but not delicate; well balanced
V	1	Aug. 30, 1939	24.5	0.90	3.50	11.6	.76	2.8	14	Fruity, distinct aroma; high tannin
IV	1	Sept. 5, 1940	23.0	1.00	3.28	11.5	.47	2.8	13	Distinct; flat; perhaps from acid reduction
V	1	Aug. 16, 1940	22.7	0.86	3.30	11.8	.52	3.1	20	Distinctive flavor, very palatable
IV	1	Sept. 11, 1941	24.7	0.97	3.29	12.3*	.56	3.1	25	Astringent; distinct aroma; slow-maturing
V	1	Aug. 15, 1941	22.8	0.67	3.37	10.8	0.53	3.2	0.24	Fruity, distinct flavor, astringent, slow-maturing
Grignolino										
V	1	Sept. 6, 1935	23.9	0.67	.	11.7	0.51	2.9	0.22	3R-5
IV	1	Sept. 13, 1936	24.2	0.49	3.52	12.4	.46	2.7	15	Orange pink, distinct flavor; tannic
V	2	Sept. 1, 1936	23.5	0.49	3.92	12.2	.41	3.5	21	Orange red; very flat, oxidizes easily
IV	1	Aug. 26, 1937	22.2	1.07	3.36	.	.	3RY-4	55	
V	1	Sept. 24, 1937	24.2	0.53	3.65	12.8	0.54	2.1	0.16	Tannic; slightly distinct, flat, orange red
								3RY-3	51	.
								3RY-o-s §	22	Typical color; tannic, distinct flavor

IV	2	Oct. 17, 1938	23 3	0.47	3 55	11 6	0.41	2 7	0 15	o.s. <sup>4</sup>	-	Tannic, rose color; flat, tenu- to -spoil Fruity; slightly distinct flavor; tannic
V	1	Aug. 31, 1938	23 8	0.57	3 45	13 6	.64	3 0	.26			
IV	3	Sept. 5, 1939	23 7	0.87	3 14	11 5	.57	2 9	12	3R-3	85	Varietal aroma, color more pink than orange Astringent; balanced, typical orangered color
V	1	Aug. 30, 1939	24 8	0.51	3 62	11 0	.67	3 2	19	3Ry-3	49	
IV	3	Sept. 4, 1940	22 2	0 95	3 22	10 8	.44	2 7	11		45	Orange-red color, fruity; flat
V	1	Sept. 12, 1941	22.1	1.06	3 18	11 4	\$3	3.1	25		90	More red than usual; tart, typically astrigent Lacks orange; tannic; balanced
V	1	Aug. 15, 1941	23 1	0 90	3 20	11 7	0 63	2 9	0 22		46	
Gros Mansenc												
IV	1	Sept. 23, 1935	21 3	0 89		10 7	0 61	2 3	0 16	3VR-36		Slightly distinct; tart, fruity, good quality
IV	1	Sept. 13, 1936	21 0	0 78	3 26	10 8	.46	2 7	16	2R-17	200	Fruity, characteristic flavor
IV	1	Sept. 26, 1937	21 0	0 87	3 42	11 1	.57	2 5	13	5VR-18	167	Balanced; standard red table wine
IV	2	Sept. 24, 1938	22 8	0 71	3 38	12 2	.61	3 2	17	3VR-32	367	Distinct flavor; above average quality
IV	2	Sept. 13, 1939	22.9	1.06	3 09	10 8	.73	2 9	.09		377	Excellent color, fruity and tart, medium distinct
IV	2	Sept. 12, 1940	21 7	1.17	3 25	10 3	.62	2 9	10		76	Tart, but rich; distinct fruity flavor
IV	3	Sept. 12, 1941	21 5	0 73	3 16	10 3	0 65	3 1	0 13		271	Fruity, good flavor, tart; good quality
Lagrain												
IV	1	Sept. 17, 1935	23 2	0 81	.	10 5	0 45	2 8	0 25	3VR-36	.	Medium distinct flavor; coarse, harsh
IV	1	Oct. 9, 1936		.57	4 14	15 0	.50	4 3	.26	R-44		Fruity, alcoholic, with raisin flavor
IV	1	Sept. 13, 1937	21 7	72	3 70	12 1	.38	2 5	17	3VR-27	333	Ordinary quality; flat (acid reduction)
IV	1	Sept. 8, 1938	19 4			9 9	.67	2 9	.21			Fruity, distinct flavor, slow-maturing, tannic
IV	1	Aug. 21, 1939	22 2		72	3 40	11 0	5 1	3 0	14		Excellent color, balance; good quality
IV	1	Aug. 19, 1940	21 9		83	3 38	11 3	.67	2 9	10		Fruity, good color; average flavor, quality
IV	1	Oct. 1, 1941	25 5	0 73	3 55	13 6	0 53	3 3	0 17		606	Intense color, ordinary flavor, blending type

(Continued on following page)

TABLE 19—(Continued)

		Mondseu												Muscat Hamburg												
		Oct.	19, 1936	20	4	0	63	10	3	0	65	2	7	0	11	2VR-13	2VR-50	2VR-25	3R-9	5VR-31	600	Medium distinct aroma; tart, above average quality Grapes slightly overripe; ordinary flavor, flat Grapes not ripe; low in acid; poor quality				
I	4	Sept. 29, 1935	25	0	0	59	12	2	36	3	0	25	2	3	17	2VR-56	455	205	Well balanced, average quality							
III	1	Sept. 23, 1935	17	.4	0	47	8	4	50	3	0	23	2	3	17	3VR-19	183	600	Alcoholic, raisin flavor, tends to spoil							
IV	1	Sept. 10, 1936	21	9	0	76	3	29	11	2	56	2	8	23	3	205	670	Heavy, harsh, slightly bitter, poor quality								
I	1	Oct. 5, 1936	24	4	0	52	3	81	12	9	59	3	3	26	3	205	600	Heavy, harsh, slightly bitter, poor quality								
II	1	Sept. 22, 1936	24	2	..	..	12	3	55	3	1	17	3	1	17	3VR-36	330	205	Well balanced, average quality							
III	1	Sept. 16, 1937	22	6	1	06	3	19	12	4	65	2	5	17	3	10	3VR-19	183	205	Distinct flavor, fruity; balanced, above average						
IV	1	Sept. 26, 1937	19	5	0	59	3	49	10	2	48	2	3	10	3	10	3VR-19	183	205	Firm, earthy, ordinary quality						
I	2	Oct. 18, 1938	21	7	0	71	3	29	11	8	66	2	9	27	4	27	4VR-36	330	205	Distinct, almost aromatic, balanced; above average						
IV	2	Oct. 1, 1938	22	1	0	47	3	40	11	9	60	3	1	25	3	25	VR-13	205	205	Fruity, slightly distinct; rather astrigent						
I	1	Oct. 4, 1939	20	5	0	59	3	23	9	7	64	2	1	10	3	10	3VR-56	455	205	Fruity, distinct aroma; balanced; good quality						
II	1	Sept. 21, 1939	21	4	0	71	3	35	10	0	58	2	6	12	3	12	3VR-19	183	205	Heavy, harsh, flat; good color; poor quality						
IV	2	Sept. 22, 1939	22	7	0	54	3	49	11	5	47	2	5	15	3	15	3VR-19	183	205	Distinct, almost aromatic, rough, heavy, average						
V	1	Aug. 31, 1939	20	3	0	55	3	18	3	18	..	..	..	..	..	..	..	..	..	..	Heavy, flat, good color; poor quality					
I	1	Sept. 22, 1940	22	3	0	84	3	18	11	9	70	2	8	17	1	17	2VR-36	330	205	Fruity, distinct aroma; balanced; good quality						
IV	2	Sept. 30, 1940	19	9	0	55	3	67	11	6	40	2	5	13	2	13	3VR-56	455	205	Heavy, ordinary quality, rather flat. A pink wine of same lots was also of ordinary quality						
V	1	Aug. 29, 1940	22	3	0	57	3	50	11	7	56	2	7	16	1	16	3VR-19	183	205	Fruity, good acid, average quality						
I	1	Sept. 28, 1941	20	5	0	99	2	91	10	5	68	2	6	17	2	17	3VR-56	455	205	Tart, spicy; coarse flavor						
II	1	Sept. 17, 1941	20	6	0	71	3	18	10	8	69	2	9	12	3	12	3VR-19	183	205	Distinct aroma, astrigent, coarse flavor						
IV	1	Sept. 13, 1941	18	1	0	66	3	10	8	7	52	1	9	20	1	9	3VR-56	455	205	Thin, must not balanced; wine astringent						
I	1	Oct. 26, 1935	23	5	0	88	..	..	12	8	0	73	2	7	0	67	Ry-5	-	-	-	-	-	-	-		
III	1	Oct. 10, 1935	22	0	48	..	11	2	38	2	5	13	3	2	10	3R-9	3R-9	3R-7	3R-7	3R-7	3R-7	3R-7	3R-7			
IV	3	Oct. 8, 1935	23	7	51	..	12	3	41	2	2	10	3	2	10	3Ry-5	3Ry-5	3Ry-5	3Ry-5	3Ry-5	3Ry-5	3Ry-5	3Ry-5			
V	1	Aug. 12, 1935	23	3	66	..	11	1	42	2	7	17	3	2	10	3R-9	3R-9	3R-9	3R-9	3R-9	3R-9	3R-9	3R-9			
I	1	Oct. 10, 1936	23	1	..	..	16	1	31	11	7	16	3	3	10	3R-13	225	225	225	225	225	225	225	225		
III	1	Sept. 8, 1936	23	9	..	..	4	07	20	1	26	10	3	05	2	7	2R-7	102	102	102	102	102	102	102	102	
IV	2	Oct. 1, 1936	26	7	..	..	16	9	36	13	5	08	3	3	15	3	15	3R-9	201	201	201	201	201	201	201	201
V	1	Aug. 9, 1936	22	0	48	..	10	7	30	3	0	15	3	3	15	3	15	3Ry-3	65	65	65	65	65	65	65	65
I	1	Oct. 7, 1937	21	5	77	3	34	11	0	66	2	7	22	2	7	22	2VR-10	170	170	170	170	170	170	170	170	
IV	1	Oct. 25, 1937	23	3	..	..	20	6	36	10	0	07	3	3	10	3R-9	77	77	77	77	77	77	77	77		
V	2	Sept. 24, 1937	24	4	..	..	3	97	12	0	33	2	3	10	3	10	3R-3	40	40	40	40	40	40	40	40	
I	1	Oct. 22, 1938	22	5	..	..	3	03	12	5	72	2	6	22	2	6	P-18	130	130	130	130	130	130	130	130	
IV	2	Oct. 11, 1938	23	7	43	3	54	20	7	43	12	1	09	3	10	09	3Ry-9	110	110	110	110	110	110	110	110	
V	1	Sept. 10, 1938	23	4	29	3	28	19	3	30	12	4	0	07	3	10	3Ry-6	61	61	61	61	61	61	61	61	

(Continued on following page)

TABLE 19—(Continued)

Region	Number of samples	Average harvest date, and year	Must				Wine			
			Balling degrees	Total acid, per 100 cc	pH	Alcohol, per cent	Fixed acids, grams per 100 cc	Tannin, grams per 100 cc	Extract, Tannin, Color intensity*	Museat, Hamburg
Museat, Hamburg—(Continued)										
IV	1	Oct. 4, 1939	24.2	0.44	3.42	17.9†	0.35	12.3	0.07	153
IV	3	Sept. 26, 1939	24.1	0.51	3.61	17.9†	.33	11.1	0.05	3Ry-6
V	2	Aug. 30, 1939	23.1	0.50	3.61	18.3†	.33	7.1	0.05	3Ry-5
IV	1	Oct. 18, 1940	23.7	0.49	3.28	13.5	4.3	3.2	17	135
IV	2	Sept. 22, 1940	25.1	0.55	3.62	20.1†	4.1	10.9	0.06	307
V	1	Aug. 29, 1940	24.8	0.48	3.72	16.7†	3.3	11.4	0.07	111
IV	1	Oct. 10, 1941	21.2	0.87	3.10	11.0	7.4	2.7	18	171
IV	2	Oct. 3, 1941	23.8	0.53	3.47	20.0†	4.3	9.0	0.10	139
V	1	Aug. 25, 1941	22.5	0.44	3.69	19.0†	0.27	10.8	0.08	30
Nebbiolo										
IV	1	Sept. 23, 1935	17.9	0.63	8.7	0.59	2.6	0.22	2VR-19	Distinct aroma; fruity, lacking character
V	1	Aug. 23, 1935	22.1	0.75	10.1	0.59	2.6	0.17	2VR-32	Varied aroma, fair flavor; ordinary
IV	3	Sept. 19, 1936	22.7	0.64	3.43	11.6	5.3	2.9	13	218
V	1	Aug. 17, 1936	21.4	0.62	10.3	4.1	2.9	12	3R-10	Slight aroma; thin, little flavor; poor
IV	2	Sept. 19, 1937	19.1	1.03	3.31	9.6	6.0	2.3	12	40
V	1	Sept. 6, 1937	22.8	0.56	3.56	11.6	5.2	2.5	14	Distinct aroma, fruity; balanced, very good
IV	1	Oct. 31, 1938	22.0	0.86	3.50	13.2	5.3	2.8	15	114
IV	4	Sept. 22, 1939	23.5	0.73	3.20	11.8	6.4	3.0	14	Gray aroma; balanced, low color; medium quality
V	2	Sept. 14, 1939	25.1	0.43	3.64	16.9†	4.1	11.3	0.09	135
IV	3	Sept. 17, 1940	23.7	0.75	3.30	11.1	6.0	2.7	12	Gray aroma; balanced, low color; medium quality
IV	2	Sept. 21, 1941	22.7	0.91	3.13	11.0	0.55	2.8	0.14	153
										Tart, slightly harsh; distinct
										Typical, perfumed aroma; deficient in color
										Slight flavor, too little color, flat
										Tart, fruity, average quality

Negrara Gatinara											
IV	2	Sept. 20, 1935	21.5	0.77	8.9	0.33	2.6	0.14	5YR-20		Plain; flat, lacks character
IV	2	Sept. 11, 1936	23.0	49	3.97	10.4	.55	3.1	15	2R-17	345 Some flavor; full-bodied; lacks finish
IV	1	Sept. 13, 1937	22.0	.95	3.46	10.5	.40	2.6	16	R-21	182 Fruity flavor, soft; ordinary quality
IV	1	Sept. 28, 1938	21.0	.64	3.36	11.1	.66	3.3	18	R-13	129 Slightly distinct; pleasant fruitiness, lacks character
IV	1	Aug. 31, 1939	24.0	.73	3.22	11.4	.54	3.0	07		333 Some flavor; fairly heavy, lacks life, ordinary
IV	2	Sept. 5, 1940	22.9	.77	3.37	10.9	.41	2.8	13		181 Slightly distinct aroma, heavy; ordinary
IV	2	Sept. 22, 1941	22.7	0.78	3.34	11.6	0.43	3.0	0.17	.	242 Little character, ordinary quality
Raboso Piave											
V	1	Sept. 16, 1936	21.1	0.60	3.23	11.3	0.54	-		2R-14	210 Fair flavor; distinct aroma; soft, balanced
IV	1	Oct. 16, 1937	22.4	0.97	3.25	10.3	.53	2.9	0.22	1R-16	187 Distinct aroma; lacks character and balance
V	1	Oct. 1, 1937	21.0	0.79	3.28	10.7	.69	2.7	23	R-24	235 Fruity; tart; distinct aroma; balanced; good
IV	1	Oct. 31, 1938	22.0	0.99	3.47	9.6	.57	2.8	12	3RY-4	100 Fruity; tart; distinct flavor, good quality
IV	1	Oct. 17, 1939	24.2	0.70	3.20	10.2	.61	2.2	08		159 Fruity; tart; distinct aroma, good quality
IV	1	Oct. 1, 1940	22.4	1.22	3.08	11.1	.69	3.2	21		232 Grapey, tart, distinct aroma, good quality
IV	1	Oct. 13, 1941	23.7	1.23	3.00	11.5	0.75	3.9	0.23		625 Grapey; tart; distinct aroma, above average quality
Saint Macaire											
II	2	Oct. 5, 1935	21.7	0.63	--	10.5	0.45	2.8	0.17	2YR-25	
IV	2	Sept. 21, 1935	21.7	.70	--	10.1	.42	2.6	.17	3R-32	
II	1	Sept. 26, 1936	24.9	.69	3.68	13.7	.68	3.4	23	1VR-100	
IV	2	Sept. 6, 1936	20.5	.71	3.78	9.5	.46	2.9	.17	4VR-27	2,500 Slightly fruity; heavy; rough, average quality
II	1	Oct. 10, 1937	21.8	.31	3.28	12.6	.65	2.6	18	5YR-61	335 Lacking character; heavy; rough, ordinary
IV	2	Sept. 29, 1937	21.5	0.73	3.78	10.9	.49	2.7	0.18	3YR-20	1,000 Fruity; heavy; some flavor; above average
											Heavy and rough; coarse; ordinary quality

(Continued on following page)

TABLE 19—(Continued)

Region	Number of samples	Average harvest date, and year	Must			Wine			Tasting record
			Total acid, grams per 100 cc.	Balling degrees	pH	Methanol, per cent	Fixed acid, grams per 100 cc.	Extract, tannin, grams per 100 cc.	
Saint Macaire—(Continued)									
II	1	Oct. 9, 1938	20.1	0.69	3.14	0.75	2.9	0.21	VR-137
IV	2	Oct. 2, 1938	21.8	0.68	3.41	12.3	5.5	3.3	3R-23
V	1	Sept. 10, 1938	21.3	0.51	3.43	12.5	5.0	2.9	3VR-32
II	1	Sept. 27, 1939	21.2	0.79	3.18	11.8	7.5	2.0	18
IV	2	Aug. 31, 1939	21.3	0.89	3.25	9.9	6.2	2.2	0.09
V	1	Aug. 31, 1939	23.0	0.56	3.20	11.1	4.0	2.7	13
II	1	Sept. 22, 1940	23.8	0.78	3.30	12.9	7.4	3.0	21
IV	2	Sept. 11, 1940	23.1	0.70	3.51	11.3	4.8	2.9	19
V	1	Aug. 29, 1940	24.5	0.60	3.52	12.9	4.9	2.8	15
II	1	Sept. 28, 1941	24.9	0.78	3.20	13.1	5.4	3.2	26
IV	1	Oct. 26, 1941	25.8	0.61	3.46	10.3	5.4	3.2	13
V	1	Aug. 26, 1941	21.5	0.71	3.32	10.8	0.56	3.0	0.19
Sangiovello									
IV	1	Sept. 23, 1935	22.1	0.82	-	10.7	0.46	2.8	0.25
IV	2	Sept. 11, 1936	23.4	0.62	3.30	11.1	4.4	3.0	17
IV	2	Oct. 1, 1937	24.1	0.61	3.51	12.3	4.5	2.6	17
IV	2	Oct. 7, 1938	23.9	0.92	3.77	12.0	4.9	3.1	21
IV	2	Sept. 26, 1939	26.5	0.72	3.49	13.3	4.6	3.1	11
IV	3	Sept. 17, 1940	22.8	1.11	3.34	11.3	5.5	3.6	15
IV	1	Sept. 26, 1941	24.7	1.05	3.23	11.5	0.62	3.5	0.17

Tannat.												Tinta Cao											
I	1	Oct. 16, 1935	21.5	0.86	11.1	0.74	2.6	0.17	2YR-66	10	2YR-80	1.000	Distinct aroma; flavor, balanced; very good										
III	1	Oct. 15, 1935	23.5	0.72	65	2.9	0.24	2.9	2YR-80	10	3VR-S5	630	Distinct aroma; flavor, astringent; good										
IV	2	Sept. 20, 1936	22.3	0.81	10.7	49	2.3	10	3VR-S5				Pleasing mild aroma, not balanced; ordinary										
III	1	Sept. 22, 1936	25.2	-	13.3	55	3.6	23	R-40				Gray taste; overripe, tannic, flat										
IV	1	Sept. 13, 1936	23.8	0.56	3.27	11.2	42	2.9	5YR-36				Fair flavor, tart, full-bodied; tannic										
I	1	Oct. 13, 1937	22.6	0.80	3.41	12.5	49	2.5	18	3YR-21			Distinct flavor, aroma; balanced; above average										
III	2	Sept. 25, 1937	24.3	0.76	3.35	12.9	45	2.9	21	VR-20			Distinct flavor; lacks balance, has character										
I	1	Oct. 16, 1938	19.8	0.74	2.92	11.8	67	2.6	15	5YR-18			Very distinct aroma; balanced; good										
III	1	Oct. 16, 1938	21.6	0.75	3.03	12.4	80	3.0	26	4YR-33			Gray; tart, full-bodied, heavy; tannic										
V	1	Sept. 10, 1938	24.9	0.57	3.26	13.9	62	3.2	26	3YR-33			Full-flavored, astringent; very heavy										
I	1	Oct. 4, 1939	22.6	0.92	3.02	12.0	71	2.5	19				Distinct aroma; fruit; well balanced										
IV	1	Aug. 31, 1939	23.5	1.17	3.17	10.6	57	3.1	13				Gray; distinct; not balanced, too heavy										
V	1	Aug. 31, 1939	24.9	0.67	3.28	11.7	66	2.8	14				Fair flavor, balanced; heavy										
I	1	Sept. 24, 1940	22.0	1.07	3.08	11.0	73	2.8	23				Distinct flavor, balanced, heavy; fair quality										
IV	1	Sept. 12, 1940	22.8	1.12	3.23	11.5	68	3.3	16				Distinct; fruity aroma, balanced; good quality										
V	1	Aug. 16, 1940	23.0	0.61	3.13	12.2	51	2.8	19				Medium flavor, full body, common										
III	1	Sept. 20, 1941	23.5	0.88	2.93	12.3	81	2.0	27				Medium distinct; fruity; above average quality										
IV	1	Sept. 27, 1941	26.6	0.88	3.21	13.4	73	3.7	31				Fairly fruity; coarse, rough, heavy										
V	1	Aug. 16, 1941	21.8	0.98	3.12	11.3	67	3.0	19				Tart; fruity; distinct; medium body and tannin										
I	1	Oct. 16, 1935	23.5	0.72	11.3	0.46	2.7	0.10	4YR-92				Vinous, some flavor, flat, oxidized										
IV	1	Sept. 22, 1935	21.0	.63	10.2	35	2.6	0.09	1R-10				Vinous, fair flavor, flat, ordinary										
IV	2	Sept. 26, 1936	23.5	57	4.16	16.61	32	12.3	0.06	3RY-7			Rather good flavor, balanced, good										
IV	2	Oct. 5, 1937	23.3	67	3.55	21.21	20	9.5	0.06	5YR-11			Distinct flavor, fairly soft; tawny, ordinary										
IV	2	Oct. 14, 1938	22.5	50	3.75	20.91	45	5.5	12	3RY-14			Gray flavor, light color, pleasant; good quality										
IV	2	Oct. 4, 1939	25.1	49	3.74	19.21	33	7.3	0.08				Good flavor; soft, slightly flat, very good										
IV	3	Oct. 8, 1940	22.8	74	3.80	17.01	41	11.4	0.08				Good flavor; rich; fruity, very good										
V	1	Aug. 20, 1940	22.8	63	3.72	20.61	41	5.7	10				Some aroma; fruity; pleasant; average										
IV	2	Oct. 8, 1941	23.9	0.71	3.61	10.61	0.40	7.3	0.11				Fruity, distinct flavor; balanced; good quality										

(Continued on following page)

TABLE 19—(Concluded)

Region	Number of samples	Average harvest date and year	Must				Wine				Tasting record
			Total acid, grams per 100 cc	pH	Alcohol, per cent	Fixed acid, grams per 100 cc	Extract, grams per 160 cc	Tannin, grams per 100 cc	Color intensity*		
Valdepeñas											
I	1	Oct. 16, 1935	20.0	0.53	9.9	0.50	2.2	0.12	2VR-27	..	Distinct, pleasant; thin, but palatable
II	1	Sept. 25, 1935	26.5	.48	14.3	.47	2.8	..	2VR-40	..	Raisin taste; heavy; astringent; ordinary
IV	3	Oct. 9, 1935	22.7	.01	11.2	.51	2.7	17	VR-16	..	Fruity; distinct; balanced, average quality
I	1	Sept. 29, 1936	22.0	.39	3.89	13.0	.36	2.0	4VR-17	225	Fair flavor; flat; rough; ordinary
II	2	Oct. 6, 1936	22.9	.67	4.01	12.7	.49	3.0	4VR-29	660	Distinct aroma; fair flavor; balanced; average
IV	1	Sept. 8, 1936	22.4	.43	4.02	10.7	.47	2.7	R-8	188	Slightly distinct aroma, fair flavor; somewhat rough
I	2	Oct. 13, 1937	24.2	.58	3.59	12.7	.37	2.7	3R-22	219	Distinct flavor; low in acid; astringent
II	2	Oct. 14, 1937	19.6	.71	3.29	10.9	.55	2.5	3R-16	255	Distinct flavor; well balanced; average quality
IV	4	Sept. 12, 1937	22.1	.62	3.63	10.9	.41	2.4	4VR-11	127	Fair aroma, flavor; lacking acid, character
I	2	Oct. 18, 1938	23.3	.58	3.37	13.3	.47	2.6	2VR-16	195	Fair aroma; heavy; tannic; low in acid
II	2	Oct. 12, 1938	20.3	.59	3.26	11.5	.48	2.3	3R-13	139	Distinct aroma; not balanced; common red
IV	4	Sept. 25, 1938	23.3	.45	3.73	12.7	.46	2.9	2VR-11	194	Good flavor, lacking acid; average quality
II	1	Sept. 29, 1939	21.7	.60	3.28	11.3	.60	2.4	..	180	Fruity; tart; some character
IV	5	Sept. 8, 1939	22.7	.57	3.49	10.7	.60	2.3	..	238	Clean flavor; good acid, but thin
I	1	Sept. 24, 1940	21.5	.68	3.32	11.4	.57	2.3	..	278	Fair aroma; thin; tannic; ordinary
II	2	Sept. 23, 1940	24.5	.61	3.55	13.3	.49	3.1	..	159	Heavy, tannic; low in acid
IV	6	Sept. 18, 1940	24.4	.51	3.63	12.7	.39	3.5	..	235	Rough; flat; ordinary red table wine
V	1	Aug. 16, 1940	20.2	.39	3.46	19.4†	.41	6.8	..	175	Fair flavor; pleasant aroma; too tannic
I	1	Oct. 7, 1941	24.5	.53	3.41	12.9	.54	2.7	..	244	Clean; average quality red table wine
II	1	Sept. 28, 1941	24.2	.57	3.23	13.0	..	2.9	..	417	Fruit and medium-distinct, astringent
IV	3	Sept. 20, 1941	22.3	.54	3.36	11.7	.52	3.0	19	549	
V	1	Aug. 25, 1941	20.4	0.54	3.42	10.6	0.57	2.6	0.17	121	Flat, fruity, but not distinctive

Zinfandel											
I	3	Oct. 19, 1935	23.7	0.79	12.1	0.69	2.9	0.11	VR-44		
II	6	Oct. 12, 1935	25.7	0.69	13.7	.57	2.9	1.1	VR-21		
III	4	Sept. 26, 1935	27.9	0.56	13.1	.45	3.1	1.6	VR-39		
IV	2	Sept. 25, 1935	23.7	0.68	11.1	.39	2.7	1.2	3VR-18		
V	7	Sept. 7, 1935	24.1	0.64	11.5	.45	2.7	1.5	4VR-19		
I	3	Oct. 6, 1936	25.5	0.07	3.61	13.6	.58	3.0	17	VR-19	388
II	8	Sept. 27, 1936	24.7	0.59	3.67	14.1	.52	3.1	14	3R-15	269
III	4	Sept. 18, 1936	21.9	0.43	3.82	11.8	.38	2.9	10	VR-8	166
IV	7	Sept. 13, 1936	24.9	0.33	3.65	13.6	.53	3.3	14	VR-13	350
V	9	Aug. 30, 1936	24.1	0.45	3.85	12.9	.47	3.3	17	3R-11	243
I	5	Oct. 10, 1937	22.4	0.78	3.40	12.5	.63	2.7	14	VR-17	210
II	4	Oct. 4, 1937	23.5	0.31	3.34	14.3	.63	2.8	14	4VR-19	247
III	2	Oct. 4, 1937	25.9	0.50	3.47	13.7	.38	2.5	13	3VR-17	182
IV	3	Sept. 26, 1937	25.9	0.59	3.56	13.2	.61	3.3	11	VR-16	171
I	2	Oct. 22, 1938	25.9	0.96	3.69	14.3	.77	3.5	19	3YR-34	290
II	1	Oct. 7, 1938	20.1	0.08	3.14	12.2	.77	2.8	18	R-19	182
III	1	Sept. 21, 1938	19.5	0.99	3.05	11.5	.71	2.5	16	R-10	93
IV	1	Sept. 21, 1938	22.8	0.55	3.58	12.2	.62	3.3	14	3R-4	
V	1	Aug. 31, 1938	21.0	0.55	3.51	12.6	.49	3.2	26		
I	3	Sept. 30, 1939	21.7	0.95	3.06	11.8	.83	2.6	11		289
II	3	Sept. 17, 1939	22.0	0.73	3.11	12.2	.69	2.7	14		183
III	4	Sept. 22, 1939	22.5	0.75	3.24	12.0	.61	2.5	9		240
IV	3	Sept. 17, 1939	20.9	0.33	3.36	10.9	.43	2.3	0.8		117
I	4	Sept. 29, 1940	21.3	1.04	3.07	12.3	.63	3.0	12		190
II	3	Sept. 11, 1940	22.9	0.84	3.41	12.5	.67	2.4	13		263
III	1	Sept. 19, 1940	23.9	0.91	3.38	12.0	.65	3.1	14		282
IV	9	Sept. 6, 1940	22.1	0.79	3.49	11.9	.41	2.7	6		141
V	2	Aug. 18, 1940	25.2	0.61	3.50	12.5	.54	3.0	13		232
I	1	Oct. 10, 1941	25.4	1.15	3.00	14.7	.89	3.5	19		323
II	2	Oct. 1, 1941	22.8	0.84	3.07	13.3	.74	2.9	14		266
III	2	Sept. 18, 1941	22.2	0.85	3.10	12.6	.68	2.9	17		250
IV	3	Sept. 18, 1941	20.0	0.91	3.26	11.0	0.58	2.7	0.11		79

\* Data in left column, by the Dujardin-Salleron vino-colorimeter; following Hilgard's procedure the observed figures have been divided into 4,000 so that the recorded figures will be proportional to intensity. Data in right column, by use of color standards and a color comparator.

† Variety identity questionable.

‡ Color too light to measure.

Duplicate lots produced pink wine of average quality.

slight resistance to phylloxera is not sufficient to survive these organisms when conditions favor them.

The vines are moderately vigorous and productive; the clusters medium-sized, long-conical, shouldered to winged, and well filled with medium-sized short-oval, thick-skinned, black berries. Ordinarily the fruit should reach the crusher in good condition. The grapes are easily crushed, and the juice yield is good.

Except for the very warm season of 1936, the acid content has been good. The pH, nevertheless, has been relatively high.

The primary value is its color. In this property the variety surpasses Alicante Bouschet, but does not equal Salvador. Its wines have possessed abundant color, but its stability as regards both the amount and the hue has not been satisfactory. Although the color has been deposited much more slowly than in Alicante Bouschet wines, it has decreased markedly in time. In several lots the hue has lost attractiveness, and the wines have become somewhat brownish.

The dry wines of Alicante Ganzin, as such, have been heavy, rather tannic, somewhat aromatic, and at best very ordinary. The dessert wines have been of similar character and quality for their type. In both types the wines have been relatively free from objectionable properties.

These wines are valuable solely for blending. For this, their principal merit is their color, a property in which they are inferior to the Salvador, but decidedly superior to products of the other red-juiced grapes. Blends for body and tannin can usually be had from varieties that are desirable for other reasons as well. The Alicante Ganzin is adapted to regions III, IV, and V. In some years its fruit would fail to ripen in regions I and II. Plantings are not recommended.

*Aramon*.—The Aramon vines are moderately vigorous, and the variety produces unusually well. In southern France it is the predominant variety for light-colored, thin *vin ordinaire*. Algerian wines of higher alcohol and body are frequently blended with it.

Except in the musts of 1935 and 1936 the original total acid content has been good in the cooler regions. The fixed acid content is by no means, however, so satisfactory, over half of the wines falling below 0.60 per cent in acid. The sugar content is uniformly low. Some difficulties are experienced in harvesting at the proper maturity. The berries are very large and are set rather loosely on a moderate-sized cluster. If clusters are handled roughly they shatter, and if left in the vineyard they rapidly become moldy. The juice yield is particularly large. The fermentations are uniformly good and, with normal precautions, clean.

Hilgard tested 20 samples of Aramon between 1884 and 1894. He considered it useful for blending because of its agreeable fresh taste and its productivity. The wine was noted to be deficient in color and tannin, and was found to mature early. The grapes were sometimes said not to ripen properly, although his analysis shows a fair Balling reading, averaging over 22° for stations in the Santa Clara Valley.

The wines produced in the present studies are characterized by their low tannin, color, body, and alcohol content, the alcohol being usually below the

amount desired for dry table wines. If the desirability of producing low-alcohol pink wines in this state should be established, the Aramon is well suited for this purpose.<sup>49</sup> No wine of quality has yet been obtained from it in any of the tests. All the samples have a distinct fruity, fresh-grape taste. The wines mature very early; in small cooperage, in fact, they are always brilliantly clear and in good condition after the second racking. If carefully prepared they will keep in glass for several years, although the improvement in quality is not commensurate with the aging.

Aramon is therefore suitable for bulk-type pink wines of low alcohol—a type not yet legally permissible in this country. It is also suitable in blending to reduce the color, body, and alcohol of heavy wines. In favored coastal locations, where it attains sufficient sugar yet keeps its acidity, it produces wines of more than bulk quality. A number of these have produced very satisfactory pink and red sparkling wines. At present, however, no further planting can be recommended. Sufficient bulk-quality table wines are produced from existing varieties and in more productive locations than the coastal areas. The variety lacks both color and acid when grown in region IV.

*Beclan*.—The Beclan has small vines. Hilgard pronounces it well adapted to cool locations and fertile soils and says it produces average crops for such conditions. He must be referring to rather special areas or perhaps to growing conditions somewhat cooler than those now used for this variety. It is highly resistant to mildew.

Beclan clusters are small, cylindrical, winged, and rather compactly set with small, round, firm, black berries. Aside from the smallness of the clusters, the fruit handles well and is crushed without difficulty.

In region I it produced a table wine well above the average in quality, differing but little from the product of region II. The wine from region I, however, was produced in 1936, a very hot season, and that from region II in 1939, an average season; hence the growing conditions were much the same considering the difference in regions. These wines were fruity, distinct in aroma and flavor, and full-bodied, with some character. They aged rather rapidly, but did not possess sufficient character and finish to be more than good table wines.

The wines of region III were still fairly well balanced, with some aroma and flavor; but they lacked character and freshness. Those of region IV were generally unbalanced, tending to be flat and to become oxidized. The wine of 1939, which had a fair acidity, was soft and of good flavor; but it, too, lacked finish.

Some of the samples from region V did not appear to be typical of the variety. This fact, however, introduces no great difficulty, for the product was entirely unsatisfactory. The table wines were deficient in acidity, body, color, and character, while the dessert wine was just another ordinary red sweet wine.

The Beclan, though a weak grower and a low yielder, produces good table wines in the proper environment. Its low yields will eliminate it from all but the very coolest areas where grapes are now grown. Possibly in the coolest locations its great resistance to mildew will make a place for it. Elsewhere it should not even be considered.

<sup>49</sup> Amerine, M. A., and A. J. Winkler. Color in California wines. IV. The production of pink wines. *Food Research* 6(1):1-14. 1941.

It is wholly unsuited to regions III, IV, and V on the basis of yield, composition, and quality. Bioletti recommended it for the coast counties only, which is correct if only an average wine is desired. It is said to blend well with the Cabernet and with certain other well-flavored, heavy-bodied varieties such as Tannat.

*Black Malvoisie*.—The Black Malvoisie is a heavy and regular bearer. Its vines are above average in vigor and thrive on a variety of soils.

Its clusters are large, long-conical, and well filled with large, long-oval, blue-black berries. On account of the shape of the berries it is frequently confused with the Barbera. The latter variety has smaller berries, and the fruit is over twice as high in acid. The skin is fairly thick, though tender; still, this fruit has been used extensively as a table grape. It withstands shipment over short distances, and its handsome appearance and pleasant flavor appeal to some consumers. In the winery it is readily crushed and yields average amounts of juice. If left on the vines until late in the season it shrivels, but rarely sunburns or raisins.

The Black Malvoisie has failed to produce a wholly satisfactory table wine anywhere in the state. It has usually been deficient in color and acidity, but these have been only two of its defects. In region I the table wines have been slightly distinct, fruity, of good flavor, but somewhat thin, and lacking in character. In this region the variety hardly matures its fruit. In the other regions the fruit attains normal maturity; but its table wines have been generally unbalanced, principally through a lack of acidity. They were poorest in region V and showed some slight improvement in cooler areas, as in going to regions IV and III.

The dessert wines have been smooth, soft, slightly distinct, well balanced, with some character, but usually with a deficiency in color. They have not had very distinct aroma or flavor, but are well balanced for red dessert wines except for their lack of color. Even so, they have surpassed the red sweet wines from other black table grapes. Their quality has not equalled that of the Grenache, the Mission, or the black port-wine varieties such as the Tinta Madeira.

On the basis of these tests the Black Malvoisie is not recommended for planting anywhere in California for wine-making purposes. Its dessert wines are its best products, but other equally or more productive varieties produce superior examples of this type. It produces average-quality table grapes together with a sound red dessert wine, slightly lacking in color. Furthermore, the grapes attain a very high sugar content without undue raisining.

*Bolgnino*.—The Bolgnino is of moderate vigor and above-average productivity. Its clusters are medium large and conical, compactly set with small, round, reddish-black berries. The fruit matures rather late. Hilgard does not mention Bolgnino until his last report and gives no data for its wines, but reports at Tulare a must with  $24.6^{\circ}$  Balling and 0.48 per cent total acid. It is possible that both he and Bioletti were familiar with it under the name of Nebbiolo Tronero. At any rate, neither variety is recommended in any of their reports.

The experience in the present studies has been restricted to samples from Guasti and from Davis. According to the must analysis in table 19, the acid content is relatively high even in region IV. There is considerable variation in

the picking dates; since the grapes are rather sensitive to overripening, it was difficult to pick them at the proper moment. The Balling readings, accordingly, vary. In a hot year such as 1936, the sugar is excessive; in other years adequate. The total acid content shows some unexplained variations; but in the main, the musts themselves are good, as the pH measurements show. The wines have been tart, fruity, well balanced, with some flavor, of average and better quality. Only in two years has their color been sufficient, the 1940 lot having only enough for a pink wine. On the whole they have tended to be slightly astringent and lacking in finish, but their composition makes them not unpleasing.

The variety can produce good standard table wines in region IV and possibly III. It will probably not ripen normally in regions I and II and will lack color and possibly acid in region V.

*Charbono*.—The Charbono, a rather weak grower except in very fertile soil, produces only moderate crops. It fruits on old and new wood and has a rather large amount of second crop. The clusters are medium-sized, loosely set with berries larger than the average. It resists mildew even in the coolest locations.

The Charbono ripens rather late, particularly in region I, where it barely reaches 20° Balling by mid-October. The acidity is good in that region, but below average in all the others. The wines have been of good color, and those from region I have been fruity and agreeably flavored. Even those of region II have been average, though with a tendency to flatness. In regions III and IV Charbono is decidedly not desirable for table wines. In one case it was tested for dessert purposes, but the quality did not justify further trials.

Hilgard<sup>50</sup> tested it in the warmer districts, where he found it productive and likely to yield an agreeable wine. By Bioletti's time,<sup>51</sup> however, the experience of the station did not justify the planting of this variety anywhere in California. The present results agree with Hilgard's: "It is not a wine to be kept long or used alone . . . It is likely to be of use, however, only to those with whom quantity is more looked for than quality." The sole possible recommendation is for planting in the more humid portions of region I for average-quality wines. Under these circumstances its resistance to mildew favors it over the Carignane; but, for the reasons enumerated, average wines probably cannot be economically produced on the marginal lands of the cooler regions.

*Fresia*.—The Fresia is another variety grown extensively in Piedmont in northern Italy. The vine is only moderately vigorous and requires longer-than-average pruning to produce full crops for its size. In Italy it is said to be more productive than the Nebbiolo, which it has replaced in some localities. Here, however, it is not productive in regions IV and V. Hilgard makes the same complaint regarding the warmer localities. It is rather resistant to mildew. The clusters are long, conico-cylindrical, and well filled. The berries are medium-small, almost round, reddish black, with a rather tough skin. The fruit matures in early midseason and tends to shrivel and raisin rather easily if left on the vines after maturation.

Since all the samples came from regions IV and V, it is obvious that the musts are very well supplied with acid. This is also reflected in the sharp red

<sup>50</sup> See citation in footnote 16, p. 496.

<sup>51</sup> See citation in footnote 18, p. 496.

color and the rather green taste. Otherwise the wines have been fairly well balanced, though somewhat high in tannin, and heavy. The flavor resembles that of the Zinfandel, being markedly fruity and berrylike; but the flavor is coarser, hardly so desirable as the best wines of the latter variety. The distinctive flavor was noted by Hilgard, who thought it possibly too pronounced for general trade popularity.<sup>22</sup> This may not be a disadvantage under present trade conditions. The use of relatively large amounts of Fresia in region IV would produce fruity and distinctive wines of good acidity, which the consumer would recognize. The quality, though not outstanding, would be recognizable. Because of their relatively high tannin content, these wines sometimes age rather slowly; but, by judicious fining, they can be made salable when young. In Italy they are frequently used within a year or two after production. The high tannin is an advantage in their early self-clarification.

The wines from regions IV and V have been only light red—a disadvantage of the variety. In a cooler location the color would be improved. This, however, would normally involve increased astringency, which would further prolong the aging period.

The wines, though above average, are not good enough to offset the low productivity and lack of vigor. Fresia is not recommended for larger-scale planting anywhere. Its special aroma and flavor, however, might well make it a part of a successful venture for a small winery in the proper location, possibly in some of the warmer coastal valleys. Its omission by Bioletti is significant in view of the varieties that he did recommend for the San Joaquin Valley.

*Grignolino*.—Wine of pink or light orange-red color is produced from Grignolino grapes in Italy, and immigrants from that country hold it in high esteem. Because of its natural high tannin content it possesses most of the characteristics of red wines. Occasionally the color is more red than orange red.

The vines are moderately vigorous and productive. The clusters are large, long-conical, well filled with medium-sized, round, reddish-black or brown berries. They mature in good condition, but do not withstand early rains. The juice yield is above average.

In the cooler seasons such as 1935, 1937, and 1939, the Grignolino grapes of region IV produced good table wines, and the product of region V was fairly well balanced. In warm years such as 1936 the acidity has been too low. The better wines had a distinctive varietal aroma and flavor, a high tannin content, and a light orange-red color. The high tannin content requires aging in wood for several years and also a heavy fining before bottling.

The Grignolino is a distinctly different wine, appealing greatly to those who like it, but not meeting with general approval. The variety should not be planted unless means and facilities are available to bring the wine to best development and bottle maturity.

According to the figures and observations recorded in table 16, this variety is adapted to region IV and perhaps to III. In region V the acidity has been too low.

*Gros Manzenc*.—Gros Manzenc is a vigorous grower. To utilize its capacity one should prune it to more buds per spur than usual; but it is not a heavy producer. The clusters are average-sized, long, well filled with medium-small,

<sup>22</sup> See citation in footnote 16, p. 496.

round, reddish-black berries. The fruit handles well, is crushed readily, and has a good juice yield. The vines are liable to attack by mildew.

Under the environmental conditions of region IV the composition has shown Gros Manzenc to be well suited for table wine. The acid content of the must varied from 0.71 per cent to 1.17 per cent—a very favorable amount for the location. With proper storage conditions a good percentage of the original acid is retained in the aged wines. (See the acid content for 1938, 1939, and 1940.)

The color content of these wines has been ample and of satisfactory hue. Tannin content has been sufficient to lend desirable stability.

These properties, together with a characteristic aroma and flavor, have given the wines distinctiveness, fruitiness, freshness, good color, and good keeping quality. In several respects Gros Manzenc resembles the Barbera wines, but apparently it matures earlier. The wines are above average in quality, particularly in region IV; but so far we have produced no outstanding wine from this variety.

The results to date show Gros Manzenc to be adapted to region IV, and it should do well in III. Here it may find a place for the production of table wines better than those from Carignane, Zinfandel, Petite Sirah, and similar varieties.

Its low production will exclude it from region V, where its quality will not be high enough to offset the smaller crops. In I and II it will be too acid to produce a balanced wine, and Hilgard reports that it failed to ripen at Mission San Jose. Bioletti recommended it for the interior valleys. The present recommendation is that Gros Manzenc will produce standard red table wines in regions III and IV.

*Lagrain*.—The Lagrain vines are of moderate vigor and productivity. The clusters are easily stemmed, being medium-sized, long, and loosely set with oval, black berries. The thin skin requires moderate care in handling. The juice yield is good.

Table wines of the Lagrain produced at Davis have possessed only moderate amounts of acid. The principal deficiencies, however, have been a rather ordinary flavor and a tendency to be coarse and rough. The very liberal supplies of color and tannin, though of value in themselves, have tended to make the wines heavy and common.

In region IV the Lagrain has been just another variety. In V it would be very deficient in acid; in cooler regions very coarse and tannic. It is not suggested for planting. Although Bioletti<sup>55</sup> recommended it for the San Joaquin Valley, apparently because of the large amount of stable coloring matter, he also noted its low acidity when grown at Tulare. The desirable qualities alone do not warrant planting, especially in view of the heavy ordinary flavor. It would occasionally prove useful in warm districts for blending to balance the color, but is perhaps unnecessary under present trade conditions.

*Limberger*.—This variety has been collected only in region I and region IV. It has been only an ordinary producer at Davis. The clusters are of moderate size, and the berries very black. The grapes seem moderately resistant to spoilage and have been crushed in good condition. The juice yield has been good.

<sup>55</sup> See citation in footnote 17, p. 496.

The Limberger ripens just before midseason and has good acidity. Unless picked at the proper time, however, it will lose much of its initially high acid. Its wines are well colored, and have a fairly coarse but moderately distinctive flavor. Under the climatic conditions of region IV it is not of high enough quality or productivity to warrant planting.

For making average wines in the cooler regions it appears to have a place. It may be used either alone for a standard red wine or in blends to give body and color. Its early ripening will recommend it to growers who desire to spread the picking season over a longer period. It will not, however, make the highest quality wines and should not be planted where the finest are desired.

Further trials should be made, since this variety was not included in the earlier tests and only two regions are represented in the present trials.

*Mammolo Toscano*.—The Mammolo Toscano matures early and has only moderate or small crops. It has never had a large crop in region V, and in two years the crop was very small. Since the vines are probably on their own roots, this scanty output appears to be a varietal weakness. The long clusters are borne on a characteristic and very long stem. The berries are pink and of medium size. The fruit is relatively clean on reaching the winery. It is easily crushed and has a very good juice yield.

Even in region V the musts have a good acidity, but they will not maintain it if left on the vines until overripe. They ferment cleanly.

The wines are distinctly fruity—apparently a unique varietal trait. Unfortunately they are deficient in coloring material and, strangely enough, high in tannin. To produce a well-balanced wine, therefore, one must age the wines for several years, during which the color becomes less and less satisfactory, taking on an orange hue. The quality, however, is good.

Mammolo Toscano should possibly be tested under cooler conditions than region V, since coolness would increase the amount of coloring material in the skins. In addition, however, the grapes would contain more tannin—decidedly undesirable. In view of the particular aging requirements, the commercial prejudice against light-colored high-tannin wines, and the small production, plantings are not recommended for general California conditions. Small acreages in regions IV and V for those who desire a distinctive red or pink table wine may be worth while.

*Mondeuse*.—The Mondeuse is a variety of good productive habits, ripening in midseason. One objection is that it does not ripen when it overbears, as it is prone to do. For this reason it should not be cane-pruned. The clusters are long, and the berries are easily removed by the stemmer. The juice yield is good, and fermentations are usually clean. Because it seldom has too much sugar, it is frequently used to blend with varieties that are overripe.

The musts of this variety are of only moderate acidity, and in regions IV and V are deficient in acidity for red table wine. The red table wines from regions I and II are well colored, fairly fruity, and distinct in aroma, tending to be almost spicy or aromatic in the cooler years. The flavor may be described as somewhat coarse, obvious, and without finesse. In the warmer regions Mondeuse produces rough, rather heavy, decidedly coarse wines of common quality.

Past usage of this variety has been mainly for blending. Since it lacks qual-

ity when by itself, this would seem to be the only rational procedure. Hilgard found Mondeuse to be chiefly adapted to region II. Bioletti endorsed it for the coastal counties and considered it useful for the production of standard red wines in the San Joaquin Valley.

It is not recommended except in I and II, and plantings there are advisable only where grapes are required for blending for the production of standard wine. The Mondeuse should not be blended with higher-quality varieties because its own flavor is too pronounced; even with Zinfandel it tends to dilute the varietal flavor of the latter.

*Muscat Hamburg*.—The Muscat Hamburg is less vigorous than Muscat of Alexandria. The fruit is oval and black. The berries are somewhat smaller than the Alexandria, and the clusters about three-fourths the size. This variety has found some recognition as a table grape, but is not much used for wine.

The composition, except in region I, indicates its usefulness for dessert or natural sweet wines, but not for dry table wines. Some of the wines from region I have been distinctive, with a perfumed aroma and good balance; but they have never been scored above average. The reason is their harshness—a common property of most muscat varieties when not accompanied by sugar.

The table wines from the other regions (III, IV, and V) have in some cases possessed a distinct aroma; but they have usually been harsh, unbalanced, and flat. The color has been very deficient—hardly enough for even a normal pink wine.

The dessert wines have, on the whole, been poorer than those of the Muscat of Alexandria. Muscat Hamburg apparently possesses a stronger muscat aroma than the latter, though the wines have not been consistent in this property. A few have been very good, but many have contained too little of the usual muscat character. The flavor has varied. Obviously, the variety is less readily handled than the Alexandria.

Several natural sweet wines of this variety were well balanced, full, rich, and fairly smooth. These have shown to better advantage than either the dry table or dessert wines. They have been almost as good as those produced by the Aleatico.

This variety may fill a place if dry, red muscat wines are to be produced in regions I or II, which is unlikely. The Muscat Canelli would produce wines of greater smoothness and delicacy in these regions, but they would not be red. It is not recommended for regions III, IV, and V, for there its wines are too low in color and are surpassed by other muscat varieties in flavor although not in aroma. The particular perfumed character may find some utilization in either region IV or V for a pink, or, when aged, a tawny dessert wine, and the possibility for using it as a table grape offers an additional attraction. At present the Aleatico is preferred.

*Nebbiolo*.<sup>64</sup>—A moderately vigorous variety, the Nebbiolo bears only moderate crops with long-spur pruning. Its clusters are medium-large, slender, and well filled with medium-small berries, which are usually reddish brown around the pedicel. The grapes crush easily and the juice yield is good.

The Nebbiolo is among the oldest and best Italian varieties. In the Pied-

<sup>64</sup> Two Nebbiolos, Nebbiolo bourgu and Nebbiolo fino, are included in this summary. A so-called Nebbiolo Tronero is listed as Bolgnino.

mont province its finest wines are usually marketed under the name of the locality where the grapes are grown.

The wines from region IV have been entirely successful. Although somewhat sharp and rough when young, they have improved more rapidly than those of the Barbera and Grignolino, and at maturity have been pleasant standard wines. Some of them rank among the best wines from Italian varieties. They portray many of the same qualities for which Nebbiolo is known in Italy.

The grapes have not had so high acidity as the Barbera; but except in 1936, which was very warm, they have had ample. The tannin content, too, has been sufficient without rendering any of the lots excessively astringent. The color content has hardly been sufficient—a disadvantage in region IV.

In region V the grapes have lacked both acidity and color, and the general quality of the wines has been much reduced. Judging from these results, the Nebbiolo is well adapted to region III and the cooler parts of IV. In areas warmer than Davis the color will regularly be too deficient.

The limited yields restrict Nebbiolo to the production of quality wines only—a fact to be duly considered when plantings are contemplated. Under present conditions the Nebbiolo should probably not be planted in California except in regions III and IV in a limited way by small producers who wish to specialize in a wine of this character.

*Negrara Gattinara*.—The Negrara Gattinara has been very little known in California, and no previous published results have been found. It ripens in midseason. Its vines are of average vigor and above-average productivity. The clusters are narrow and long, thickly set with small, oval, jet-black berries. The fruit is easily crushed, and the juice yield is good. Mildew may be difficult to control in the less arid regions.

The musts have varied in composition. The acidity was very satisfactory in 1935 and 1937, cool years, but was far too low in the hot season of 1936. The pH, however, has not been excessive.

The dry table wines from region IV have been disappointing. Despite a mild distinctiveness, they have lacked finish and character and have been heavy, with a tendency to be flat and plain. Their color content was sufficient.

The variety is not recommended for general planting. In region III, with very careful harvesting, above-average quality standard red table wines can be produced. Further tests along these lines are indicated.

*Raboso Piave*.—The Raboso Piave is grown in northeastern Italy. It is a vigorous grower but only a moderate producer with spur pruning. The clusters are medium-large, long-conical, often winged, and rather compactly set with medium-large short-oval berries. The fruit is firm and has reached the crusher in good condition each year. It matures very late, the average picking date being October 15 at Davis.

Its musts from regions IV and V have been very well balanced for dry table wines. Except in the very warm season of 1936, they have retained high acidity with moderate amounts of sugar. Their pH has been relatively low.

The wines have been distinct in aroma and flavor, refreshing, well balanced, but not definite enough in character and finish to be distinctive. Nevertheless, they have been interesting products for warm regions. They aged rather

slowly, but were free of handling difficulties, and kept well once they had reached maturity. The color intensity fits the variety better for pink than for red wines.

The Raboso Piave will not mature its fruit regularly in regions I, II, and III. Its only moderate productivity will handicap it in IV and V, but its high acidity may make it useful. Under these special conditions, therefore, it may be valuable in the latter areas.

*Saint Macaire*.—The Saint Macaire is grown to a very limited extent in one of the regions of lesser importance south and east of Bordeaux, France. It has been distributed rather widely in California. Its total acreage, however, is small, although it was recommended by Bioletti for planting in the interior valleys.

Saint Macaire is only fairly vigorous and moderately productive. Its clusters are medium to large, short-conical, shouldered, and sparsely to moderately well filled with medium-sized, roundish berries. The grapes sunburn in warm locations in the foothills. This is particularly true in dry seasons when the grapes lose their leaves. Otherwise they usually reach the winery in good condition. The grapes are easily crushed and the juice yield is good.

Even in region IV the musts have been fairly well balanced for sugar and acid. They fermented without difficulty to produce heavy, rough, full-bodied wines of about average quality. None of them manifested any marked delicacy, and all lacked smoothness of finish. Their principal value, especially in region II, is their acidity and their intense color. Besides these properties they have a high tannin content.

The wines from region II have in some years shown good balance, fair smoothness, and some character. Those of regions IV and V were also among the better heavy red dry wines of their type produced in these regions. But these latter wines have regularly lacked definiteness and character.

In general the Saint Macaire wines have required long aging, which their quality at maturity does not warrant. As blending wines, however, their acid, color, tannin, and body may have real value in regions IV and V. For blending, this is among the most promising varieties tested in region V. Here, too, its general quality is better than that of the Alicante Bouschet, Grand noir, and Petite Sirah that have been tried in the past. Where better grapes such as Petite Sirah and Tannat are adapted, their wines will be more desirable for blending because of superior quality and distinctive character.

The Saint Macaire may be said not to be adapted to regions I and II. It has produced its best wines in II, but there it has not equalled many other equally productive varieties. In region IV it has been surpassed by several others. It shows promise for blending in region V, where its wines have possessed the best combination of acid, color, tannin, and body of the varieties tested. Still its quality is only average, and because of its poor viticultural characteristics—moderate vigor, average production, and sunburning—only restricted plantings should be made, and these only for blending in standard red wines under region IV and V conditions.

*Sangioveto*.—The vines of Sangioveto are moderately productive, somewhat above average in vigor. The clusters are medium-large, slender, well filled with small, oval berries. The fruit is clean, withstands handling well, and yields an

average amount of juice. The grapes ripen in midseason and have a high acidity. The pH is moderately low for the climatic conditions of region IV.

On a whole, the table wines produced from Sangioveto in region IV have been well balanced and good. The variety is well supplied with acid, has ample tannin, but lacks color. The wines possess a pronounced berrylike aroma and flavor. In consequence they have been distinctive and fruity, and—for the most part—well balanced. Some samples have lost a large amount of acidity during storage, apparently because of the activity of acid-reducing micro-organisms.

The Sangioveto should do well in regions III and IV, but it does not produce sufficiently large crops for economical bulk-wine production. Its wine does not have the finish of the better French varieties, but the distinctive character makes it useful for growers who wish to produce a special type. In region V it will lack acid and color, while in regions I and II it matures too late and with too great an acidity. On account of the restricted amount of color it may have to be blended with varieties of greater color even in regions III and IV. This would conform to the practices of the Tuscany district of Italy. Refosco and Tannat are acceptable for blending.

*Tannat.*—The Tannat grows vigorously, produces well above average crops, and usually shades its fruit sufficiently. The clusters are medium-large, strongly shouldered, and closely set with medium-sized, short-oval, black berries. Some small green-shot berries are generally present, but these are usually not crushed in wine making.

The wines of Tannat from the north coastal areas—regions I and II—have been of unusual interest—richly endowed with a distinctive aroma, full pleasing flavor, good balance, intense color, and a full body. Their tannin content has been near maximum year after year. In region I these wines were full, well rounded, of considerable character, delicate, and of high quality. Those of region III were somewhat heavier, a bit coarser, much more tannic, and only average in quality.

These wines have matured somewhat slowly; that is, they have tended to retain a degree of roughness and astringency longer than those of most of the better varieties. The intense color persists and retains its desirable hue. Once mature, these wines have kept well. The fact that this quality does not appear to be associated with high alcohol content should be important in itself, since most California table wines suffer in quality from their very high alcohol.

Wines of the Tannat grown in regions IV and V were, as a rule, heavy, somewhat coarse, and less well balanced. Aroma and flavor, too, were less distinctive and pleasing. Here its wines would usually be of value only in blending, for which their high tannin content, good acid, and heavy body fit them well, though unfortunately they add little quality to the blend. Several wines of the warmer areas, for which less mature fruit was used and which were therefore lighter, showed good quality. Care in timing the harvest apparently means better wine. Thus a good product may be secured in region III.

The Tannat is well adapted to cool areas. In areas as warm as region III, especial attention must be given to the time of harvest. It matures in midseason and should be harvested promptly, since its best wines are those of only moderate alcohol content. It will not equal Cabernet Sauvignon under similar

conditions, but its wines are distinctive and very good in these areas, and it is more productive. The vinification is singularly free of difficulties. It is recommended for region II for the production of standard red table wines.

In regions IV and V, Tannat will not regularly produce a balanced table wine. Its value there would be for blending, which when used appropriately may offer possibilities. With the usual harvesting and vinification procedure, however, the Tannat from these regions will add little other than color, tannin, and body to the blend.

*Tinta Cao.*—Tinta Cao, though vigorous, is only moderately productive. Its clusters are medium-sized and loose to well filled, with small berries. The fairly tough skin, together with the open clusters, makes it much more resistant to unfavorable weather and rot than most red wine-grape varieties. The vine is relatively resistant to mildew. The juice yield is barely average.

Both the source of the Tinta Cao (the Douro Valley of Portugal) and the composition of its fruit under our conditions indicate its adaptation for dessert wines. When it is used for these types, the wines are above average—well balanced, soft, and pleasant. Their flavor and aroma, though not too definite, are distinctive. The wines of very ripe grapes tend to be somewhat heavy and rough, a fault that can be overcome by earlier harvesting or by blending. The color is pleasing, but rather light for present demands; some blending may be necessary.

Tinta Cao is not suitable for dry-wine production. Even in our coolest environment, region I, the acid content is too low for table wines. The same is true of the tannin and color content.

The variety is admirably suited to regions IV and V, where it will produce large vines and, if pruned properly, moderately heavy and regular crops. The size of the clusters and the type of pruning required will increase production costs slightly, but the wine is of good quality. It is not, however, recommended above Tinta Madeira, which gives wines of excellent color and equally good flavor and is at present preferred. For red dessert wines the Tinta Cao ranks above such varieties as Carignane and Alicante Bouschet.

*Valdepeñas.*—The Valdepeñas, introduced from east central Spain, was not included in the variety tests by this station in the 1880's. Several plantings were made, however, in more recent years. Bioletti stated:<sup>58</sup> "Of all the varieties which the station has tested in the interior valleys, that which combines the largest number of good points as a dry wine grape is the Valdepeñas. The wine made from it has always been satisfactory."

The Valdepeñas ranks with the most vigorous and productive of grape varieties. The clusters are large and irregularly shaped. They vary from long-conical, shouldered, to very full or heavy in the middle. The berries also vary, some being very small, the majority medium; many are flattened at the end and are broader than long. The pulp is firm, and the skin is sufficiently tough to resist handling injuries. With normal crops the fruit matures early. The grapes crush easily, and the juice yield is above average. This variety is rather susceptible to mildew and red spider.

The present tests do not completely confirm Bioletti's opinion of the wines. Regularly the musts of well-matured Valdepeñas grapes have been too low in

<sup>58</sup> See citation in footnote 17, p. 496.

acid to produce dry table wine of good balance and quality. Less than 20 per cent of the must samples showed over 0.6 per cent acidity even when the samples of all regions are considered. In fact, the acidity did not show a definite correlation with region of production. This condition was probably an effect of excessive crop in the warmer regions; if so, it could be corrected.

About all that can be said for this variety is that the products were clean, average-quality, red table wines. In the cooler regions they tended to be fresher, more pleasing in aroma and flavor, whereas in the warmer regions, especially in the warm seasons, they were decidedly flat, heavy, and rough, with hardly enough color. They matured rapidly, without difficulty, and may be considered as typical standard-quality bulk wines.

The red sweet wines of the Valdepeñas have been too astringent for the type. Possibly further tests should be made with dessert wines.

Since this variety will produce only standard table wines in regions I, II, or III, it cannot be recommended. Even on the rich level valley soils the quality of its wines are surpassed by that of other productive sorts. In the past it was supposed to have made outstanding wines in certain coastal locations, but such claims find no support in results reported here. In region IV it may well be considered for bulk wines because of its vigor and productivity.

*Zinfandel*.—The Zinfandel has attained commercial recognition in California. It was brought in with the earlier importations after the mission period; but when, whence, and by whom remain a mystery.

The vines are not vigorous in the sense of attaining large size. Nevertheless, they are productive. The clusters are large and usually heavily winged. Often the wing may attain such proportions that the two parts are of almost equal size, producing a characteristic double cluster. The berries are medium-large, round to slightly flattened lengthwise, reddish black to black, with a large scarlike area at the apical end. The skin is thick, but not too tough. Although Zinfandel was popular and was shipped extensively during the Prohibition era, its fruit is not particularly resistant to handling injuries.

The fruit ripens unevenly: some berries may be partially raisined while others have not reached maturity. In the warm regions and in most areas in hot years complete raisining occurs in a considerable percentage of the fruit by the time the average Balling reading of the free-run juice of the normal berries in the cluster indicates normal maturity. Since the color is closely correlated with maturing, it, too, is very irregular.

Another defect is the tendency of the clusters to be overcompact. The berries may be so crowded that some are pushed loose from their stems and others are crushed in the final stages of maturity. Thus decay-causing organisms obtain a start. Sometimes the center of a cluster is a rotten mass at harvest time, and the whole cluster has an acetic odor. Once berries break and release their juice it is impossible to control the organisms.

In regions I, II, and III the fruit is, as a rule, well balanced for table wines. It must, of course, be harvested at proper maturity. These wines possessed in marked degree the characteristic fruity, raspberrylike, aromatic flavor.

In regions I and II the wines tended to be somewhat overly tart in the cool years and not too well balanced. Aroma and flavor were rich, delicate, and clean if the grapes reached the crusher in sound condition.

In the warmer locations of region II and in region III the wines have been uniformly the best balanced, fullest, and most drinkable. They contain most of the richness and delicacy of the aroma and flavor of the cooler regions, and in addition these qualities are fuller and more harmonious. When produced of sound, well-matured, but not overripe or raisined fruit, these table wines were really above average. Even here, at their best, they still lack the finish and character required of the finest wines.

In region IV these wines were less well balanced, had a somewhat less pleasing flavor, and were seldom entirely free of overripe grape or raisin flavors. They were only ordinary to standard.

The table wines from region V were coarse in aroma and flavor, deficient in acid, harsh, alcoholic, and with a fairly pronounced raisin taste.

Because of its irregular ripening and its tendency to raisin, the fruit of the Zinfandel has usually produced cleaner-tasting pink wines than standard red wines. This was true especially in regions IV and V, but perhaps also in the other regions during hot seasons. These pink wines are fresher, livelier, and cleaner in aroma and flavor because of the much restricted period of fermentation on the skins.

In considering the Zinfandel for planting, one must think not only of its productivity and the readily recognizable characteristics of its wine, but also of its usual condition at harvesting. Only with the greatest care can unsound or raisined grapes be kept out of the fermentation tanks. This difficulty is not of recent origin: Hilgard in 1892, referring to these defects, stated:<sup>56</sup> "It is not, therefore, without good cause that its popularity is decreasing, and that sturdier, and on the whole, higher grade varieties are gradually taking its place in the planting of new vineyards." Despite this and other statements on its poor quality, large plantings have continued. Approximately half the present acreage, however, was planted during the Prohibition era, when the quality of a wine was only a secondary consideration. Numerical predominance at present does not indicate merit on a quality basis.

Although its wines in regions I and II are of very acceptable table quality when produced of sound fruit, the Zinfandel cannot be said to be adapted to these areas, except possibly in the warmer parts of II. In some years, the fruit does not mature before the autumn rains, and it is more or less severely attacked by bunch rot in these seasons.

The fruit attains best development on well-drained soils in the warmer locations of region II and in III. Here raisining occurs, but the fruit can usually be harvested before the rains. The Zinfandel is much overplanted at present. Further plantings, if made, should be restricted to regions II and III, and then made only for the production of an average-quality wine.

The Zinfandel should not be used to produce table wine in regions IV and V. Its fruit is badly sunburned, and much raisining usually occurs before the fruit is mature for harvesting. Under irrigation the berries are large, and bunch rot is all too common. In these regions the variety has attained some favor for the production of bulk port. Nevertheless, these wines are usually badly marred by the defects of the fruit at harvesting, and better quality can be obtained from other varieties.

<sup>56</sup> See citation in footnote 15, p. 496.

## VARIETIES NOT RECOMMENDED

Numerous varieties of wine grapes are so devoid of merit that they cannot be recommended anywhere in California under present conditions.

The varieties listed here fail to warrant planting for several reasons. The most common objections are lack of sufficient sugar, acid, or both, poor production, and susceptibility to rot or diseases. Some varieties listed here have flavor, but are so inferior to other closely related varieties in quality or production that they need not be considered. Although such grapes are not recommended, the data and the observations which have brought about their rejection are of great value. This is the only available information about most of them. It accordingly forms the sole basis for sound decisions regarding the utilization of the present stands of these varieties and for their evaluation in the future.

### WHITE VARIETIES NOT RECOMMENDED

White varieties not recommended include Bambino bianca, Clairette blanche, Feher Szagos, Green Hungarian, Hibron blanc, Hungarian Millennium, Kleinberger, Malmsey, Marsanne, Mathiasz y-ne, Mourisco branco, Muscat Pantellana, Muscat Saint Laurent, Nasa Veltliner, Nicolas Horthy, Palaverga, Pavai, Roussette, Saint Emilion, Sauvignon vert, Selection Carriere, Steinschiller, Terret, Vermentino Favorita, and Vernaccia bianca. The analyses of musts and wines of these varieties for various regions are given in table 20.

*Bambino bianca*.—The Bambino bianca is a vigorous grower and heavy producer. Since it ripens late in the season, it is adapted only to conditions as warm as those of Davis, region IV, or warmer sections.

Its clusters are very large, loosely set with small, round, thin-skinned berries. The grapes do not crush easily, however, and the juice yield is below average. The fruit, despite its late ripening, reaches the crusher in excellent condition.

Although slightly aromatic, its wines, as produced at Davis, were badly balanced, harsh, and of very poor keeping quality. The variety is decidedly not suited for table wines, lacking acidity in region IV and ripening too late for planting in cooler regions. Its undesirable aromatic property, harshness, and plainness of flavor condemn its use for any wines. It is not recommended anywhere in California.

*Clairette blanche*.—The vines of the Clairette blanche are vigorous and productive in a suitable environment. When the weather is unfavorable at blooming, its clusters may be susceptible to coulure. It produces well only in the warmer districts, and the crop is usually unsatisfactory in region I.

The clusters are medium-large, conical, shouldered, and well filled with medium-sized, oval berries. The fruit is firm and fairly crisp. It withstands handling very well, and the juice yield is good.

Only in region I did the grapes of Clairette blanche contain enough acid for well-balanced table wine. But the fruit matured too late; it was not fully mature by mid-October. As a result, its wine here was of very light though not unpleasant character. It would hardly pass as a well-balanced product.

The wines of region II were lightly distinct, pleasant, fairly well balanced, and of average quality. Although somewhat lacking in character, they were nevertheless nice, simple wines that should find a place in everyday consumption.

In regions IV and V the wines became softer and fuller in body, but flat, with a tendency to spoil.

In region II these wines were a marked improvement over Green Hungarian and Palomino and might displace these varieties if average white table wines are desired. Unreliable productivity in the cooler regions was noted, however, by Hilgard and Bioletti; and the Clairette blanche is not recommended. It will not mature normally in all years in region I. In regions III, IV, and V its wines are so generally unsatisfactory that it should not be planted.

*Feher Szagos*.—The vines of the Feher Szagos are very vigorous and produce large crops. The clusters are large and long-conical, loosely filled with large, long-oval, greenish-yellow berries. The skin is too thin and tender to withstand rough handling. The grapes must be crushed as soon as possible after picking.

During periods of high relative humidity or showers shortly before harvesting, many berries may crack at the apical end. In the hotter parts of region V the cracked berries may dry up; but in region IV they regularly become infested with rot organisms, and deterioration sets in. If left on the vines too long the grapes begin to shatter badly. The juice yield is good.

As indicated by the acid content of its musts and wines, the Feher Szagos is not suitable for table wines. Every lot has been flat, unbalanced, and deficient in flavor, tending to spoil or become sherrified even if the grapes were from the coolest regions.

For sherry material the variety has shown itself to somewhat better advantage. These wines have been fairly neutral, but smooth, of good character and average quality. They have aged rather rapidly.

Although the sherry types of the Feher Szagos have been smooth, mellow, and average, the usefulness of the variety is very definitely limited by the cracking of its fruit. It should not be planted anywhere except in parts of region V. Even there, in some years, its fruit reaches the crushers in very poor condition. The Palomino surpasses it in all respects except perhaps productivity and rate of aging.

Hilgard was likewise unimpressed with this variety; and Bioletti specifically wrote,<sup>77</sup> "Don't plant . . . Feher Szagos, . . . which makes poor wine."

*Green Hungarian*.—The Green Hungarian has been popular in regions II, III, and IV because of its great vigor and its productiveness; but the wines are very poor. The vine is singularly free of troubles, but the fruit is rather thin skinned and subject to rot during early rains. The clusters are large, conical, and well filled with medium-large round berries. The fruit is easily crushed, and the juice yield is satisfactory.

This variety can be differentiated from the Palomino on the basis of its upright growth, its round almost entire leaves, and the regular conical shape and greater compactness of the clusters.

(Text continued on page 618)

<sup>77</sup> See citation in footnote 18, p. 496.

TABLE 20  
COMPOSITION OF MUSTS AND WINES OF WHITE VARIETIES WHICH ARE NOT RECOMMENDED

Region	Number of samples	Average harvest date and year	Must			Wine					
			Balling degrees	Total acid, grains per 100 cc	pH	Alcohol per cent	Fixed acid, grains per 100 cc	Extract, grains per 100 cc	Tannin, grains per 100 cc	Color intensity*	Tasting record
Bambino bianco											
IV	1	Oct. 7, 1937	24.4	0.56	3.68	13.2	0.38	2.1	0.09		Slightly aromatic, harsh, flat, poor
IV	1	Oct. 31, 1938	22.2	55	4.00	12.4	35	2.1	0.4	22	Slightly distinctive, very flat, poor quality
IV	1	Oct. 16, 1939	25.7	47	3.68	14.7	43	2.9	0.5	22	Slightly aromatic, harsh, heavy, very flat
IV	1	Oct. 8, 1940	23.7	52	3.75	13.5	48	2.4	0.3	25	Little character, very ordinary
IV	1	Oct. 29, 1941	22.7	0.59	3.51	12.5	0.42	2.3	0.04	7	Neutral, thin, not suited for dry table wine
Clarette blanche											
IV	2	Oct. 1, 1936	19.4	0.45		10.0	0.33	2.0	0.07		Dry, sweet, fruity taste, flat, ordinary
II	1	Oct. 14, 1936	23.6	48	3.29	13.6	45	2.1	0.1		Well balanced, pleasing, distinct aroma
IV	1	Sept. 13, 1936	23.0	35	3.41	12.7	31	2.4	0.3		Soft, full; flat, average quality
I	1	Oct. 10, 1937	19.6	51	3.20		56				Tart, little character; ordinary quality
IV	1	Sept. 26, 1937	21.6	55	3.60	11.9	36	1.6	0.4		Oxidized, very flat, tends to spoil
II	1	Oct. 28, 1938	22.3	65	3.11	12.0	62	2.8	0.5	22	Slightly distinct, balanced, average character
IV	2	Sept. 20, 1938	22.3	52	3.42	12.8	49	2.4	0.5	12	Gassy, rich flavor, flat, oxidized, ordinary
II	1	Sept. 23, 1939	21.7	58	3.19	12.2	52	1.5	0.3	32	Slightly fruity, ordinary character
IV	2	Sept. 1, 1939	21.1	64	3.21	10.7	43	1.8	0.3	17	Delicate flavor, flat, tends to spoil
IV	1	Aug. 20, 1940	22.4	66	3.48	12.7	53	1.9	0.2	14	Some flavor, fruity, average quality
V	1	Aug. 16, 1940	18.3	39	3.46	10.5	39	2.0	0.3	9	Distinct, early-maturing, flat, not balanced
I	1	Oct. 7, 1941	23.0	54	3.25	12.6	56	2.0	0.4	6	Fair flavor, lacks acid, oxidized, average
IV	1	Sept. 22, 1941	21.8	0.76	3.30	11.7	0.59	2.4	0.07	18	Well balanced; ordinary flavor

\* For footnotes to table see page 617.

## Feher Stagasz

IV	1	Oct. 13, 1935	20.1	0.40	10.3	0.32	2.1	0.04	
V	3	Aug. 24, 1935	21.1	0.53	10.4	0.41	2.1	1.2†	
I	1	Oct. 5, 1936	21.5	32	3.95	12.3	43	2.1	0.03
IV	1	Sept. 25, 1936	24.2	40	3.92	12.8	41	2.5	0.03
V	2	Aug. 14, 1936	21.2	42	3.61	16.1†	27	8.1	0.06
V	1	Oct. 12, 1937	18.2	31	3.60	10.6	40	2.0	0.05
V	1	Sept. 28, 1938	23.5	39	3.58	20.71	31	2.6	0.03
V	1	Aug. 28, 1940	20.5	41	3.50	19.64	40	4.4	0.05
I	1	Sept. 28, 1941	17.9	66	3.19	10.2	59	1.9	0.07
IV	1	Oct. 13, 1941	25.4	0.60	3.64	20.31	0.40	4.0	0.04

## Green Hungarian

I	1	Oct. 17, 1935	17.0	0.40	9.4	0.42	1.6	0.05	Very light in body, character, ordinary
II	3	Oct. 4, 1935	19.1	37	3.9	2.0	0.03		Tart, thin, little character, ordinary
III	1	Oct. 2, 1935	18.3	48	45	2.0	0.04		Unbalanced, thin, tends to spoil, poor
IV	2	Oct. 1, 1935	19.3	36	8.7	36	1.9	0.08	Lacks flavor; very light in body, poor
I	1	Oct. 7, 1936	35	3.56	10.2	36	1.8	0.03	Very light color, body, little flavor, ordinary
II	4	Oct. 1, 1936	20.3	29	3.88	10.5	33	2.7	Very simple and undistinguished, watery. Sparkling wine of a duplicate lot was very ordinary
III	1	Oct. 2, 1936	20.2	36	3.31	10.8	30	2.8	Little flavor or color, average quality. Sparkling wine of a duplicate lot was very ordinary
IV	1	Sept. 25, 1936	21.1	3.37	11.5	51	2.4	0.04	Little character, not unpleasant, common
I	1	Oct. 21, 1937	18.0	52	3.36	9.8	35	1.6	Flat, thin, little flavor, poor quality
II	4	Oct. 11, 1937	18.3	53	3.42	10.2	38	1.9	Flat, little flavor; too neutral.
IV	1	Oct. 2, 1937	19.7	42	3.76	9.9	25	1.9	Very little flavor, very flat, no quality
V	1	Sept. 9, 1937	18.9	55	3.70	9.6	28	2.1	Thin; devoid of character, not balanced, poor
II	1	Oct. 23, 1938	16.3	48	3.12	9.7	51	1.7	0.06
II	3	Sept. 24, 1939	19.4	57	3.34	9.7	61	1.9	10 Slightly fruity; thin; musty; ordinary
II	1	Sept. 22, 1940	20.3	0.49	3.40	11.9	0.46	1.9	21 Slightly distinct; flat; ordinary quality
							0.02	10	

(Continued on following page)

TABLE 20—(Continued)

Rogron	Number of samples	Average harvest date, and year	Must			Wine					
			Balling degrees	Total acid, grains per 100 cc	pH	Alcohol, per cent	Fixed acid, grains per 100 cc	Extract, grains per 100 cc	Tannin, grains per 100 cc	Color intensity*	Tasting record
Hiltron blanc											
IV	1	Oct. 9, 1935	20.1	0.68	..	10.2	0.48	2.2	0.03	Slightly distinct aroma; not balanced; spoils easily	
IV	1	Oct. 10, 1936	21.7	.51	4.23	11.7	.26	2.9	.03	Very flat; slightly distinct aroma; soft; poor	
IV	1	Oct. 25, 1937	24.0	0.53	3.66	13.5	0.20	2.2	0.03	Very flat; more of a sherry material; common	
Hungarian Millennium											
IV	1	Oct. 9, 1935	22.0	0.46	..	11.1	0.47	2.3	0.05	Thin; flat; fair, slightly distinct flavor	
IV	1	Oct. 17, 1936	22.7	.40	3.97	12.6	.37	2.8	.03	Soft; flat; distinct, ordinary flavor	
IV	1	Oct. 3, 1938	20.3	.44	3.52	12.7	.46	3.7		Average quality; flat, little character	
IV	1	Oct. 3, 1939	22.7	.44	3.46	22.01	.41	2.5	.02	Cooked and uncooked samples with rancio flavor	
IV	1	Oct. 15, 1940	22.2	0.44	3.80	16.74	0.37	10.1	0.06	Medium sweet sherry material, good balance	
Klemberger											
II	1	—, 1935	20.3	0.62		11.7	0.40	2.5	0.06	Slightly distinct aroma, flat; above average	
IV	2	Sept. 20, 1936	20.3	41	3.78	10.3	.49	2.0	.03	Slightly distinct, fruity flavor, tends to spoil	
IV	2	Sept. 2, 1936	20.3	51	3.73	11.6	.39	2.3	.03	Very light; flat, little flavor, oxidizes	
IV	1	Sept. 20, 1937	21.8	51			.40	2.0	.02	Slightly distinct; very flat; ordinary quality	
II	1	Oct. 5, 1938	20.2	.48	3.14	11.1	.55	2.7	.06	Moderately distinct; lacks character, ordinary	
IV	2	Sept. 24, 1938	23.1	.55	3.71	12.3	.57	2.7	.07	Slightly aromatic flavor; heavy, little character	
										One wine was green in color	
IV	1	Aug. 16, 1939	20.5	.92	3.29	10.0	.53	2.2	.04	Thin; not balanced; slightly distinct, ordinary	
V	1	Aug. 31, 1939	22.8	.50	3.48	11.8	.53	2.3	.03	Distinct, soft, rich, oxidized	
IV	1	Aug. 28, 1940	20.4	.79	3.42	11.4	.67	2.5	.03	Recognizable aroma, fruity, average quality	
IV	2	Sept. 16, 1941	21.6	0.65	3.45	11.7	0.61	2.5	0.06	Neutral; ordinary quality, balanced	

		Malmsey											
		Oct. 19, 1935	22.0	0.50	4.00	20.6†	0.28	2.5	0.03	...	...	...	...
IV	1	Oct. 17, 1936	21.7	.46	3.88	18.9‡	0.36	13.0	0.02	97	97	Balanced sherry material; sherrifies	Flat, becomes amber, tends to spoil
IV	1	Oct. 15, 1940	29.5	.45	0.44	3.62	18.2†	0.23	9.6	0.04	5	Distinct flavor; aromatic, good quality	Neutral flavor; ordinary quality
IV	1	Oct. 30, 1941	24.5	0.44									
		Marsanne											
		Sept. 26, 1937	23.2	0.54	3.74	12.5	0.33	1.9	0.03	...	...	Soft; distinct; balanced; lacks delicacy	...
IV	1	Sept. 24, 1938	23.0	.44	3.65	12.0	51	2.5	0.07	24	24	Distinct flavor; aroma, balanced; ordinary	...
IV	2	Sept. 12, 1939	21.9	.62	3.35	11.6	38	2.0	0.03	23	23	Slightly distinct; light; pleasant, but ordinary	...
IV	2	Oct. 13, 1940	23.0	.50	3.82	18.1†	29	11.6	0.02	...	...	Neutral; lacks character, very flat	...
IV	2	Sept. 26, 1941	22.9	0.61	3.50	13.9	0.44	2.5	0.06	19	19	Neutral; little character; flat; earthy; poor	...
		Mathiasz y-ne											
		Sept. 28, 1938	22.9	0.42	3.88	19.1†	0.39	11.7	0.06	...	...	Rich muscat; fruity, pleasant; average	...
IV	1	Sept. 20, 1939	26.5	.51	3.80	20.7†	33	13.8	0.05	66	66	Fruity; flavorful; rich, fairly smooth, too dark	...
IV	1	Oct. 1, 1940	24.7	.57	4.10	18.5†	.24	18.5	0.04	23	23	Distinct muscat, fruity; soft and rich, average	...
IV	1	Sept. 26, 1941	27.0	0.32	4.01	20.9†	0.20	11.5	0.09	45	45	Medium muscat; soft and rich, ordinary	...
		Mounisco branco											
		Sept. 17, 1936	18.5	0.46	...					...	...	Light, thin; very little character	...
IV	1	Sept. 30, 1936	20.4	33	3.99	11.2	0.28	2.1	0.03	...	...	Plain vinous; flat, oxidizes easily	...
V	2	Sept. 13, 1936	21.3	35	..	11.0	0.25	2.3	...	...	...	Very little aroma; flat; ordinary quality	...
IV	2	Oct. 4, 1937	22.2	.57	3.77	11.1	43	2.1	0.03	...	...	Lacks flavor; slightly rough, poor quality	...
V	1	Sept. 24, 1937	21.0	.47	3.80	10.6	39	2.2	0.03	...	...	Some flavor; bland; common	...
IV	1	Oct. 31, 1938	21.2	.39	3.87	12.7	29	2.2	0.04	30	30	Slight aroma, soft; very flat; sherry material	...
IV	1	Oct. 16, 1939	23.5	.35	3.83	20.9†	31	3.1	0.02	61	61	Flat, average sherry taste	...
IV	1	Oct. 3, 1940	22.7	0.36	3.85	19.7†	0.29	6.9	0.01	43	43	Fruity; fairly good sherry flavor	...

(Continued on following page)

TABLE 20—(Continued)

Region	Number of samples	Average harvest date, and year	Must			Wine							
			Balling degrees	Total sugar, grams per 100 cc	pH	Alcohol per cent	Fixed acid, grams per 100 cc	Extract, grams per 100 cc	Tannin, grams per 100 cc	Color intensity*	Tasting record		
Muscat Puntellana													
Muscat Saint Laurent													
Nassa Veltliner													
IV	1	Oct. 17, 1939	23.5	0.51	3.57	12.9	0.33	2.3	0.03	21	Distinct muscat; flat, poor character		
IV	1	Oct. 9, 1940	24.9	57	3.76	18.21	20	14.2	0.01	55	Distinct muscat; very flat, not balanced, ordinary		
IV	1	Oct. 29, 1941	25.7	0.62	3.61	13.6	0.53	2.7	0.05	14	Distinct muscat; balanced, common character		
IV	1	Sept. 21, 1938	25.0	0.30	3.90	18.4†	0.31	12.0	0.05	16	Distinct muscat; rich, fruity flavor, average		
IV	1	Sept. 25, 1939	28.0	37	3.78	20.1†	20	14.4	0.02	63	Distinct muscat; rich, soft; flat		
IV	1	Oct. 1, 1940	27.2	46	3.82	20.7†	27	14.2	0.05	41	Fresh, luscious; perfumed muscat, good		
IV	1	Sept. 30, 1941	27.0	0.46	3.63	19.5†	0.34	12.9	0.09	11	Special muscat flavor, average quality		
IV	1	Oct. 3, 1938	21.0	0.51	4.00	11.5	0.51	1.9	0.04	11	Fruity, light, common		
IV	1	Oct. 25, 1939	21.5	45	3.52	11.7	28	2.0	0.02	14	Light, without character, flat, poor		
IV	1	Oct. 15, 1940	21.7	51	3.80	21.8†	27	5.5	0.03	44	Slight nutty sherry flavor; balanced, average		
IV	1	Oct. 29, 1941	21.3	0.51	3.64	12.1	0.42	2.0	0.04	5	Neutral, light, very common		

Nicolás Horthy									
IV	1	Sept. 28, 1938	25.4	0.53	3.97	19.8†	0.38	12.4	0.09
IV	1	Sept. 20, 1939	28.5	67	4.18	20.3‡	48	14.6	0.8
IV	1	Oct. 1, 1940	25.0	50	4.00	21.4‡	24	13.1	0.5
IV	1	Sept. 26, 1941	27.9	0.47	4.12	20.4‡	0.27	10.5	0.09
Palavergas									
IV	1	Oct. 8, 1935	23.0	0.65	11.1	0.48	2.3	0.02	Slightly fruity; little flavor; common
IV	1	Oct. 10, 1938	24.3	49	3.63	13.6	36	2.4	0.4
IV	1	Aug. 16, 1939	21.4	55	3.40	10.1	43	1.9	0.3
IV	1	Sept. 16, 1940	25.0	51		21.0‡	.31	6.7	0.3
IV	1	Sept. 30, 1941	25.6	0.63	3.51	14.6	0.56	2.7	0.07
Paval									
IV	1	Oct. 31, 1938	18.8	0.46	3.85	10.3	0.41	1.5	0.05
IV	1	Oct. 17, 1939	21.4	46	3.40	11.2	44	2.1	0.2
IV	1	Oct. 25, 1940	20.1	41	3.72	20.0‡	29	3.6	0.4
IV	1	Oct. 22, 1941	21.4	0.47	3.60	12.1	0.42	1.9	0.04
Roussette									
II	1	Oct. 9, 1935	20.1	0.44		10.6	0.46	1.8	0.03
III	1	Oct. 7, 1936	18.2	42		9.6	43	1.6	0.3
II	1	Sept. 26, 1936	21.7	34	3.40	12.6	43	2.2	0.3
II	1	Sept. 22, 1937	19.3	77	3.29	10.3	50	1.9	0.3
III	1	Oct. 19, 1937	19.7	60	3.29	11.1	42	2.1	0.3
II	1	Sept. 28, 1938	20.3	71	3.11	12.1	52	2.1	0.5
III	1	Oct. 4, 1938	18.0	43	3.01	10.5	60	2.2	0.5
II	1	Sept. 23, 1939	21.8	54	3.08	12.0	60	2.0	0.5
III	1	Sept. 22, 1939	22.4	63	3.05	12.0	61	2.3	0.6
V	1	Aug. 31, 1939	20.7	0.41	3.42	10.0	0.47	1.9	0.03

(Continued on following page)

TABLE 20—(Continued)

Region	Number of samples	Average harvest date and year	Must			Wine				
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol, per cent	Fixed acid, grams per 100 cc	Extract, grams per 100 cc	Tannin, grams per 100 cc	Color intensity*
Saint Emilion										
III	1	Oct. 10, 1935	19.8	0.60		9.3	0.63	1.9	0.05	
IV	1	Oct. 6, 1935	21.3	0.60		9.5	0.40	2.3	0.04	
III	1	Sept. 22, 1936	22.7	.68		12.5	.65	2.5	.03	
V	1	Aug. 9, 1936	20.0	.51		10.1	.29	2.6	.06	
III	1	Oct. 3, 1937	17.7	.66		3.24	10.9	.55	2.0	0.02
V	1	Sept. 9, 1937	17.9	.63		3.90		.27	2.1	0.04
II	1	Oct. 28, 1938	25.0	.83		3.09	14.0	.63	5.2	.07
III	2	Oct. 4, 1938	19.5	.53		3.28	11.5	.50	2.5	.07
IV	1	Oct. 18, 1938	20.8	.59		3.38	11.6	.46	2.4	.06
V	1	Aug. 31, 1938	21.0	.49		3.75	12.4	.50	2.6	.06
III	1	Sept. 19, 1939	23.0	.80		3.10	11.3	.46	2.0	.05
IV	3	Sept. 27, 1939	23.5	.58		3.68	11.7	.36	2.1	.03
V	1	Aug. 30, 1939	21.1	.51		3.50	10.4	.50	2.1	.03
II	1	Oct. 9, 1940	24.4	.72		3.22	14.3	.49	3.3	.04
III	1	Sept. 19, 1940	22.6	.73		3.50	12.0	.37	2.3	.03
IV	1	Oct. 3, 1940	22.5	.77		3.50	11.7	.35	2.5	.06
V	1	Aug. 30, 1940	22.9	.51		3.65	11.8	.49	3.2	.05
III	1	Sept. 20, 1941	25.0	.66		3.30	13.4	.70	2.7	.08
IV	1	Oct. 27, 1941	23.1	.67		3.48	12.4	.56	2.7	.04
V	1	Aug. 25, 1941	19.3	0.67		3.50	10.9	0.60	2.3	0.05

Sauvignon vert.											
I	3	Oct. 10, 1935	22.1	0.61	.43	-	11.1	0.39	2.4	0.07	
II	4	Oct. 2, 1935	24.8	.57	-	11.8	3.6	2.3	0.3		
III	3	Oct. 2, 1935	22.1	.53	-	11.2	5.1	2.1	0.04		
IV	2	Oct. 1, 1935	19.3	.53	.97	33	3.3	1.8	0.03		
V	1	Sept. 4, 1935	25.4	.50	-	10.9	36	2.7	0.05		
I	3	Oct. 1, 1936	21.9	.54	3.50	11.8	.54	2.4	0.03		
II	3	Sept. 19, 1936	23.2	.35	3.84	12.7	.39	2.6	0.03		
III	2	Sept. 28, 1936	23.5	.37	3.90	13.5	.35	2.6	0.03		
IV	1	Sept. 13, 1936	23.0	.38	3.61	12.5	.46	2.5	0.03		
V	3	Aug. 9, 1936	21.0	.50	3.90	11.9	.30	2.7	0.03		
I	4	Oct. 30, 1937	21.4	.71	3.40	11.9	.46	2.1	0.03		
II	3	Oct. 5, 1937	24.6	.54	3.53	14.3	.41	2.6	0.03		
III	5	Sept. 27, 1937	22.4	.65	3.63	12.5	.42	2.3	0.03		
V	2	Aug. 27, 1937	23.2	.60	3.87	12.1	.49	2.0	0.03		
I	2	Oct. 24, 1938	21.6	.54	3.35	13.3	.46	2.4	0.05	15	
II	3	Oct. 20, 1938	22.2	.55	3.33	12.4	.40	2.2	0.05	21	
III	3	Sept. 23, 1938	20.5	.36	3.59	11.7	.44	2.3	0.05	19	
IV	2	Sept. 22, 1938	23.7	.47	3.79	13.0	.47	2.7	0.05	21	
V	3	Sept. 23, 1938	22.1	.42	3.71	12.4	.42	2.7	0.07	27	
I	5	Oct. 10, 1939	21.8	.61	3.28	12.2	.49	2.0	0.03	23	
II	5	Sept. 18, 1939	22.3	.63	3.43	12.3	.51	2.0	0.02	18	
III	3	Sept. 11, 1939	23.4	.49	3.45	12.1	.50	2.3	0.03	15	
IV	3	Sept. 11, 1939	24.1	.54	3.67	10.9	.37	2.4	0.02	20	
V	3	Aug. 22, 1939	24.3	.42	3.63	11.0	.39	3.3	0.02	16	
I	1	Sept. 18, 1940	20.6	.61	3.30	11.5	.46	2.1	0.01	19	
II	4	Sept. 26, 1940	23.2	.55	3.57	13.3	.49	2.7	0.03	21	
III	2	Sept. 4, 1940	22.4	.50	3.57	12.1	.45	2.5	0.03	12	
IV	1	Oct. 3, 1940	24.6	.63	3.92	12.4	.47	3.5	0.03	102	
V	2	Aug. 18, 1940	24.5	.47	3.68	12.8	.48	2.2	0.03	10	
I	1	Oct. 10, 1941	21.0	.80	3.22	12.5	.66	2.2	0.03	3	
II	1	Sept. 17, 1941	21.1	.69	3.43	12.0	.65	2.2	0.06	4	
III	2	Sept. 13, 1941	22.2	.57	3.42	12.7	.64	3.3	0.09	12	
IV	2	Oct. 8, 1941	24.6	.76	3.67	11.7	.49	3.0	0.06	16	

(Continued on following page)

TABLE 20—(Concluded)

Region	Number of samples	Average harvest date, and year	Must			Wine			
			Balling degrees	pH	Total acid, grams per 100 cc	Alcohol, percent	Fixed acid, grams per 100 cc	Extract, grams per 100 cc	Tannin, grams per 100 cc
Selection Carrier									
III	1	Sept. 25, 1935	20.7	0.46	10.7	0.34	2.1	0.06	Thin, little flavor, very ordinary quality
III	1	Sept. 18, 1937	21.1	.67	3.58	10.8	37	2.0	0.03
IV	1	Sept. 11, 1939	24.2	.45	3.82	12.2	40	2.2	Thin, neutral, tends to spoil, ordinary
IV	1	Sept. 5, 1940	19.1	.50	3.82	10.1	36	1.9	0.01
IV	1	Oct. 2, 1941	19.6	0.45	3.79	10.8	0.35	2.0	Thin, slightly distinct, average quality
Sten-schiller									
IV	1	Nov. 5, 1935	21.5	0.60	..	12.1	0.51	2.3	0.04
IV	1	Oct. 1, 1936	21.3	.35	3.48	11.5	40	2.2	Light, fruity, plain, ordinary quality
IV	1	Oct. 10, 1938	21.2	.37	3.55	12.4	45	2.1	Light; pleasant; common character
IV	1	Sept. 25, 1939	21.5	.40	3.41	12.8	46	2.1	Slightly fruity; neutral, flat, below average
IV	1	Oct. 8, 1940	22.3	.42	3.68	12.3	43	2.3	Fruity, pleasant; refreshing, average quality
IV	1	Sept. 29, 1941	22.7	0.55	3.57	13.4	0.54	2.1	Pleasing flavor, slightly flat, poor

Terret									
IV	1	Oct. 17, 1936	19.9	0.53	11.3	0.46			No aroma or flavor, very ordinary
IV	1	Nov. 3, 1937	18.3	63	10.7	47	2.0	0.03	Little aroma or flavor; no character; flat
IV	1	Oct. 3, 1938	18.2	68	3.83	9.0	58	1.8	Light, thin, common character
IV	1	Oct. 2, 1939	22.7	49	3.50	12.4	49	1.9	Very plain flavor, not balanced ordinary
IV	1	Oct. 28, 1940	19.2	55	3.60	11.6	30	2.4	Plain and characterless, lacks acid
IV	1	Oct. 23, 1941	24.2	0.63	3.49	13.8	0.43	2.4	Neutral, lacks acid and flavor

Vermantino Favonita									
IV	2	Oct. 1, 1935	21.3	0.62	9.7	0.48	2.4	0.03	Pleasant, distinct flavor, thin; average quality
IV	1	Sept. 13, 1936	21.0	34	3.73	11.9	39	2.2	Good aroma, unbalanced, flat, tends to spoil
IV	1	Oct. 3, 1938	22.8	53	3.71	13.1		3.0	Mild aroma, fair flavor; balanced, lacks character
IV	1	Oct. 3, 1939	23.8	63	3.50	18.54	34	2.1	Good sherry; fair in aroma, flavor, soft
IV	1	Oct. 9, 1940	25.6	52	3.63	17.1†	29	15.9	Rich, full-bodied sherry, average quality
IV	1	Oct. 13, 1941	27.2	0.65	3.56	20.3‡	0.43	6.1	Pleasant, neutral sherry, good must

Vernaccia bianca									
IV	1	Sept. 17, 1936	22.1		13.3	0.34			Heavy, soft, flat, ordinary quality
IV	1	Sept. 13, 1937	21.6	0.67	3.65	12.6	25	1.9	Slight flavor, plain, flat; average
IV	1	Oct. 3, 1938	21.0	41	3.54	12.4	44	2.1	Fruity, balanced, common character
IV	1	Sept. 8, 1939	22.7	.62	3.30	12.0	45	1.8	Fruity flavor, slight aroma, soft, balanced
IV	1	Oct. 8, 1940	22.6	44	3.68	18.6‡	29	8.3	Slightly fruity, plain, ordinary, sweet sherry
IV	1	Oct. 13, 1941	25.4	0.64	3.50	20.7‡	0.36	6.6	Slight flavor; flat, average quality

\* Determined in a color comparator using an arbitrary color standard made from Eastman ABC dyes, the color intensity increases as the figures increase.

† Determined on skins.

‡ Fermentation arrested by the addition of grape brandy.

The figures for the Balling degree and acid content of the musts shown in table 20 offer convincing proof that this variety cannot produce a balanced table wine. No sample was fully mature; yet not one contained as much as 0.60 per cent acid, and only four of the fourteen were above 0.50 per cent.

In fact, the variety possesses few desirable qualities. The wines have been thin, flat, lacking in flavor or character, and poor to ordinary in quality.

On the basis of its wines the Green Hungarian cannot be recommended for planting anywhere in the state. This confirms Bioletti's 1907 recommendation. Even in blending, these wines will add only bulk; and they will dilute the possible good properties of wines with which they are blended.

*Hibron blanc*.—This variety has been tested only in region IV. Its musts have been deficient in acid for white table wine and not sufficiently high in sugar for dessert wine. Although somewhat distinctive in flavor, it is not sufficiently so to be recognizable. The variety is only a moderate producer and, in view of the poor quality of its wine, plantings are not recommended for any California conditions.

*Hungarian Millenium*.—The Hungarian Millenium is a good producer. It ripens late in the season and generally reaches the winery in good condition. The berries are very firm, and the juice yield is average. Because of the large crop the grapes do not reach a high degree of sugar under region IV conditions. The variety is very low in total acid; and the dry table wines made from it in 1935, 1936, and 1938, although palatable, were unbalanced and mediocre. The sherry material produced in 1939 and 1940 was satisfactory in flavor; but the wines were not of high enough original sugar concentration for producing heavy-bodied sherries.

The Hungarian Millenium is not recommended for California even though the flavor and character are fair for the production of sherry. Conceivably, conditions warmer than those of region IV would increase the sugar concentration sufficiently to make it useful but the acid would be further reduced.

*Kleinberger*.—The Kleinberger, when grown in regions II, IV, and V, has no promise for making good dry table wine. The grapes tested agree with the description of Hilgard. Apparently it is not a Riesling variety. It is, however, a good producer in this state.

The grapes are very thin-skinned; and under unfavorable climatic conditions, a large portion will rot before ripening. The spoilage in the vineyard is so noticeable that the variety can sometimes be recognized at a distance by the off-smell. The clusters are medium-sized and are very difficult to handle without undue injury.

The juice yield is very good, but fairly large quantities of sulfur dioxide must be used to secure a sound fermentation. Even so, there are large enough amounts of oxidizing enzymes in the spoiled grapes to give the finished wine an amber color. Despite these difficulties the wine has shown a surprisingly uniform distinctive flavor, though not of high enough quality to recommend it greatly. An important objection has been the consistently low acidity of the must and wine.

This grape is not recommended, since other varieties are cleaner and more distinctive. Furthermore, its use for Riesling wine should be discontinued, since the product does not have the proper character or composition.

*Malmsey*.—The Malmsey ripens late and has produced excellent crops. The clusters are large, and the oval berries above average in size, rather firm, though the skins are not thick. The juice yield is average. Malmsey is comparatively free from rot during ripening, usually reaching the crusher in excellent condition.

The wines produced from this variety have been too few to give a clear picture of the possibilities. It is entirely unsuitable for dry table wine, having a low acidity, but appears useful for sweet dessert wines. In sherry material its aromatic, almost-muscat flavor would probably be objectionable, although it is traditionally used for sweet Madeiras in the Madeira Islands. The flavor, however, is not a strong muscat and develops only when the grapes are fully ripe.

No plantings are recommended; the variety ripens too late to be considered for localities cooler than region IV. It is obviously the same variety tested by Hilgard, who also found it productive, but of low acidity.

*Marsanne*.—The Marsanne is a vigorous, moderately productive variety. Its clusters are large, winged, and compactly set with small, round, thin-skinned berries. The fruit is not too resistant to handling injuries and will rot under unfavorable weather conditions. Both the vine and its fruit are rather susceptible to mildew.

The wines have not been successful in region IV. Despite fair aroma and flavor, their general balance has not been good. Some of them equalled or surpassed those of Burger of the same area; others were less good. The variety should possibly be tested further to determine if there are areas to which it is really adapted. Hilgard, however, having tested it in region II, failed to find a district where its acidity was sufficient for table wines. Bioletti<sup>18</sup> must have erred in recommending it for the interior valleys for table wines, since Hilgard had endorsed it for such districts only as a sherry material. In a previous report<sup>19</sup> Bioletti does not mention the Marsanne in a review of varieties suitable for interior-valley conditions. Aside from lack of distinctiveness, its main defects are low acidity and the high pH of its musts—common shortcomings of the undistinguished varieties. Marsanne is not recommended for California.

*Mathiasz y-ne*.—The Mathiasz y-ne is a new variety from Hungary. It has a rather unusual everbearing habit; that is, it produces another crop of clusters whenever new lateral shoots are formed during the growing season. Its first crop may be about ready to mature, the second crop the size of peas, the third crop blooming, while rudimentary forms for the fourth crop are just taking shape. Since each crop requires nourishment, the quality and quantity of the main crop are reduced by competition with the second and later crops. In some seasons the second crop matures; but the third and fourth never mature at Davis. The chief disadvantage of large amounts of second crop lies in the resultant delay in harvesting. If the first crop is left on the vines until the second crop is ripe, the fruit is shriveled and frequently raisined. If the first crop has to be harvested separately, the picking costs are greatly increased.

Another disadvantage is the russet-pigmented thick skin. The grapes must be pressed immediately in order to get a light color; but by early pressing, the already small juice yield is reduced further, and the amount of muscat flavor extracted from the skins is also restricted.

<sup>18</sup> See citation in footnote 18, p. 496.

<sup>19</sup> See citation in footnote 17, p. 496.

The muscatels produced of this variety in region IV have been fairly smooth, rich, and full-bodied. Aroma and flavor, however, have been less pleasing or pronounced than those of several other muscat varieties—for example, Muscat Canelli and Orange Muscat. Although these musts and wines were very low in acid and very high in pH, little difficulty with spoilage was experienced, probably because the grapes were clean and were carefully handled in the winery and because the fermentation was arrested by the addition of grape brandy before deterioration could set in.

In view of its unsatisfactory bearing habit and its commonplace wines, this variety cannot be recommended.

*Mourisco branco*.—This variety ripens late. It has been an average producer in region IV. The clusters are large and well filled with large, soft, and fleshy berries. The fruit matures in good condition despite its late ripening. The grapes are easily crushed, and the juice yield is above average. The total acid is very low, and the pH high.

The table wines from regions IV and V have been commonplace, with no properties of particular interest. On the whole they were only vinous in flavor, lacked balance, and tended to oxidize. Their extreme flatness and neutrality is a severe disadvantage.

For sherry production the variety shows up somewhat better. Its wines, treated by the usual California sherry process, reveal a sufficient-to-good sherry flavor, together with acceptable balance. These sherries have been pleasant, with some promise, but have not developed the superior qualities secured from Palomino grapes. The white dessert wines have had little flavor and have been too low in acid even for a sweet wine.

Although resembling in composition and appearance several varieties from the Jerez region of Spain, the product of Mourisco branco as sherry is poor. Its performance to date does not recommend it for planting anywhere, even though Biolley endorsed it for dessert wines. The present results support its use in the Douro Valley, its region of origin, where it furnishes table fruit. In California it cannot qualify even for this purpose.

*Muscat Pantellana*.—The Muscat Pantellana, a vigorous grower, has produced large crops at Davis. The clusters and berries are large, the skin thick, the texture hard and crisp. The juice yield is below average for free-run juice. The grapes ripen late and have a mildly aromatic muscat aroma. The musts are of moderate acidity and, for a muscat, of below-average pH.

The wines have not been particularly distinctive. They possessed only a mild aromatic aroma. The dry wines were flat, without character, and decidedly unharmonious, while the muscatels were harsh, with a somewhat undesirable flavor. In general they portray the lack of finish characteristic of the wines from table grapes.

On the basis of results to date, this variety cannot be recommended for wines. Its possibilities as a table grape are receiving consideration.

*Muscat Saint Laurent*.—The Muscat Saint Laurent vines are only average in vigor. Under Davis conditions neither the quality nor quantity of the fruit has equalled that of Muscat Canelli or Orange Muscat. The clusters are small; the berries larger than average. The grapes are thin-skinned and must be handled very carefully. The juice yield is above average.

The wines, though rich in aroma and flavor, have lacked acidity and balance. The acid content of both the musts and the wines has been very low. Possibly these have been among the smoothest muscat wines we have produced. Smoothness alone, however, is not all-important.

Since this variety does not equal in quality or production the other well-tested and recognized muscats, it is not recommended.

*Nasa Veltliner*.—The Nasa Veltliner has been tested in region IV. There it is a vigorous-growing, productive, late-ripening variety. Its musts have been of low sugar and acidity; the dry table wines were very neutral, lacking in character, and poorly balanced. They were only plain and ordinary. One sample when baked took on a slight nutty, sherrylike flavor, and was well balanced. Nevertheless, it was only standard dessert wine.

Since its wines have not made a place for it even as a heavy producer, it does not belong in regions IV and V. Further testing would be desirable to determine its possible adaptation to II and III, but there its possibilities are limited by its late maturing. It is not recommended.

*Nicolás Horthy*.—This is another importation from Hungary, where it is of recent origin. In several respects it resembles the Mathiasz y-ne; the remarks on the disadvantage of the everbearing habit of that variety largely apply here, although to a lesser extent. The grapes when ripe are also russet pigmented. The first crop ripens in midseason. The acidity is low; the pH uniformly high. The first crop has had a good sugar content.

The wines have possessed a pleasing muscat aroma and have been rich, luscious, and fairly well balanced. They have aged rapidly, but have tended to darken unduly. These have been average muscatels.

The variety is not too vigorous or productive. Its crops have barely equaled Muscat Canelli, which is usually considered a poor producer, and have averaged less than the Mathiasz y-ne under comparable field conditions. The first crop fruit is also very subject to raisining. Largely for this reason, the condition of the fruit arriving at the crusher has never rated above fair. The variety is not recommended.

*Palaverga*.—The Palaverga is moderately vigorous and productive. It ripens in midseason. Its medium-large clusters are well filled with medium-sized berries. It handles well, is readily crushed, and gives a good juice yield.

In region IV the fruit is poorly adapted for dry table wines, the product tending to be flat, neutral, and decidedly lacking in character. A lot of sherry material that was baked developed a distinct aroma. Still, though clean and delicate, it was only a plain sherry. Further tests should probably be made.

This variety to date has failed to show any promise for wine production. It is mentioned but not tested by Hilgard, and is not endorsed by Bioletti. It cannot be recommended for planting in California. Its only possibility is as a sherry base; but in this regard the wines show too little promise, except in composition.

*Pavai*.—The Pavai has large clusters and berries and at Davis has been a good producer. Since the skins are thick and the texture is very pulpy, the juice yield is small. The grapes ripen late, but remain in good condition. The musts are very low in acid.

The dry table wines from region IV have been very common—practically

neutral, with little or no character, and particularly flat. A baked sample possessed a mild sherrylike flavor, was soft, clean, and balanced; but it, too, was only average.

This variety is decidedly not adapted for producing either table or dessert wines in region IV. It would be still poorer in a warmer area, because of its low acidity. It was not promising enough to warrant further testing in cooler regions, where, indeed, it would fail to ripen normally. It is not recommended.

*Roussette*.—Roussette is a vine well above average in vigor and productivity. The grape ripens late. The clusters are medium, short-conical or pyramidal, and well filled with medium-sized, long-oval fruit. The yellow-green berries usually take on a pinkish blush at maturity. The semiupright and open habit of growth may expose them to the sun; but sunburn has not been a factor in the regions from which grapes were obtained, except in V.

On the whole, the wines have not been unpleasant; but they have possessed little distinctive flavor or character. They might be called bland wines. Some samples were slightly thin, and others were lacking in balance; but these were not serious deficiencies. The light color was retained unusually well.

Since most of the grapes came from regions II and III, the limited acidity of certain samples is noteworthy. Other almost neutral varieties, such as *Folle blanche*, are much better balanced.

On the basis of these results it is difficult to see where the Roussette might justify a place for itself. It is not productive enough for regions IV and V; and for regions II and III other varieties of equal or greater productivity, which make better wines, should be preferred. Its chief merit is its resistance to disease, but this is insufficient to recommend it for planting. In region I the grapes will probably fail to ripen.

*Saint Emilion*.—The Saint Emilion (also known as the Trebbiano in Italy and as the Ugni blanc in some parts of France and Algeria) is moderately productive and ripens late. The clusters are large, very long, and characteristically branched at the end of the cluster. The berries are medium-sized and rather soft, with an easily broken skin. They must be transported to the winery very soon after harvesting. When overripe they sometimes have a slight pinkish bloom. The juice yield is high, sometimes almost equaling that of Burger.

This variety has produced only ordinary wines in regions II, III, IV, and V. In IV and V it is always too low in acidity for white table wines; products have frequently been better balanced as sherry material, but are rather thin for this purpose. In regions II and III the variety has occasionally yielded a light, neutral-flavored, early-maturing wine, but also sometimes a flabby, easily oxidized, common product. Because of its neutral character it is better adapted for blending than for producing a wine by itself.

Saint Emilion is not now recommended for California. Its lack of acidity and its neutral character are primarily responsible. Neither Hilgard nor Biolletti was able to recommend it.

*Sauvignon vert*.—The Sauvignon vert is widely distributed in California. It ripens slightly before midseason and in most locations is a good producer. The clusters are long and rather straggly. The berries are medium-sized, spherical, and accompanied by a large number of shot-berries. The skin is very thin and, as the grape ripens, becomes brownish on the exposed side. The

grapes are very subject to rot in wet seasons and locations and also to attack by insects. Their quality for crushing is often unsatisfactory.

This variety has been tested throughout California. Irrespective of the region it has been very deficient in acid, the only exception being two of the 1941 samples. This observation confirms the published analysis of Hilgard, who reported an acidity as low as 0.22.

The wines have had a marked tendency to spoil, owing to the very high pH of the musts. The flavor is common and lacks softness. The aroma is almost always very distinct, frequently being very aromatic and sometimes even having a muscat quality. Because of the low acidity the wines frequently have a harsh aftertaste.

Of the commonly planted white wine grape varieties of California the Sauvignon vert least deserves a permanent place. Its musts are unbalanced, and its fruit is poor. The wines are undesirable in flavor as well as composition. Several attempts have been made to utilize the variety as a sherry base and as a white sweet wine. It makes a pleasant Angelica type, and its tendency to oxidize suits it fairly well for sherry material. In neither case, however, is it outstanding; other varieties are more useful. The low acidity and the high sugar content suit the variety somewhat better for natural sweet wines, where a slight muscat flavor is somewhat less objectionable than in a dry wine. Semillon and Sauvignon blanc are, however, much better for this purpose.

No plantings of Sauvignon vert are recommended for California.

*Selection Carriere*.—The Selection Carriere is a high-producing variety, ripening late. The medium-large berries are loosely borne on a moderate-sized cluster. The vines, though but fairly vigorous, are comparatively free of diseases. The grapes from regions III and IV were very low in total acid and of only average Balling degree. They were also very high in pH.

The wines have been uniformly neutral, of only moderate alcoholic content and of very low acidity. This variety is therefore devoid of interest. In regions cooler than III it will seldom ripen sufficiently for table wines, and it is too flat and neutral for region III or IV. Its high pH makes it difficult to ferment and keep. It is not recommended.

*Steinschiller*.—The Steinschiller is of moderate vigor and productivity. Its grapes ripen very late but resist unfavorable weather unusually well. This fact, however, is of little value in California, for the variety will not ripen here in cool enough regions to retain its acidity. Its vines are markedly resistant to disease.

The clusters are small and rather short. The berries, about medium in size, turn almost russet at maturity. The juice yield is below average.

In the interior it produces only common table wines of little interest. Under these conditions it is very deficient in acid. None of its qualities would justify planting. In region II it will probably ripen too late to produce balanced commercial wines.

*Terret*.—The Terret is vigorous and productive. Its fruit ripens very late, but remains in good condition until mature. The juice yield is fair. The grapes have some pigment in the skin and must be pressed immediately after crushing.

Wines of the Terret gris and Terret blanc grapes grown in region IV were

without promise—almost devoid of aroma, flavor, or character, and thin and flat.

In region V the fruit might attain a higher sugar content, but this would be effected by a reduction in acidity. The Terret will probably not mature in region II or III. It is not recommended.

*Vermentino Favorita*.—The Vermentino Favorita is distinguished from the Malmsey (Vermentino) by its larger berry size and its less pronounced flavor. Its grapes are fairly small and round, whereas those of the latter are large and oval. The aroma also is more pronounced and possibly more delicate than that of Malmsey. The vines are vigorous, but only moderately productive. The fruit matures relatively late.

The dry wines from region IV have been of only average quality—low in acid, disappointing in aroma and flavor.

The sherries have been much more promising—pleasant, clean, and full-bodied, of good quality.

Vermentino Favorita is not adapted for producing dry wines in region IV. The quality has not been sufficiently high, and the production is low. Although productivity may be improved by longer pruning, the result may be an undue delay in the maturing of an already late-ripening sort. The wines may be of higher quality in the coastal areas; but this point would have to be proved, and the bearing under the cooler conditions determined. In regions I and II the variety would not ripen regularly and uniformly.

Although the extra aroma and flavor of the sherry is very pleasant, Vermentino Favorita cannot be recommended for sherry making in region IV because of its limited production.

*Vernaccia bianca*.—The Vernaccia bianca was once grown extensively in northern Italy and southern Austria, where it produced bulk wines. Since it starts growth late in spring, Hilgard thought it might be useful for frosty locations. Bioletti does not mention it.

This variety ripens in midseason. At Davis it has produced good crops, maturing in good condition. The clusters are of average size; the berries greenish-white or mottled. In region IV the grapes have reached the crusher in good condition and have given a good juice yield. The musts have been of less than average acidity, and their high pH reflects this condition.

At Davis the table wines have been flat and plain, lacking in flavor and aroma. They have failed to reveal in sufficiently marked degree any characteristic to indicate that the variety may be improved by a cooler climate. In region IV the dessert wines were lacking in character and flavor—too neutral to be more than ordinary. Vernaccia bianca cannot be recommended.

#### RED VARIETIES NOT RECOMMENDED

Red varieties not recommended include Alicante Bouschet, Antibo, Aspiran noir, Black Hamburg, Black Prince (Rose of Peru), Blaue Elbe, Bonarda, Chauche noir, Chenin noir, Coristano, Criolla Mesa, Criolla Vino, Croetto Moretto, Dolcetto, Early Burgundy, Grand noir, Grec rouge, Grosse blaue, Kadarka, Koptcha, Lambrusche Langhre, Lenoir, Macaroli, Marzemino, Mataro, Meunier, Negro Amaro, Neiretta, Pagadebito, Petit Bouschet, Petite

Verdot, Pfeffer, Picpoule noir, Pinot Pernand, Pinot Saint George, and Tinta amarella. Table 21 gives the analyses of musts and wines of these varieties.

*Alicante Bouschet*.—The distinctive features of this variety are well known. The leaves, characteristically curved down, are shiny. During the summer and fall they usually turn red. The fruit is black, with a heavy bloom; the juice red. The clusters are medium-large, with the berries set compactly, but not sufficiently so to cause serious breakage. The juice yield is good. Ripening is in midseason, and the vine is a good producer.

The musts in region I are very acid, but the grapes fail to ripen sufficiently. The wine is highly colored. In regions IV and V the fruit fails to retain so much acid, and the wines are frequently flat. The aroma is slightly aromatic, not particularly desirable. The wine is usually rough and somewhat harsh.

The chief attraction has been the highly colored musts, which can be drawn off almost any time after crushing. Unfortunately the color is not stable; almost immediately, it begins to precipitate, a very inconvenient occurrence in bottled wines. Dessert wines stored for years may become tawny through the precipitation of so much color. These wines are very ordinary.

This variety came to be widely planted in California before 1918. It was particularly sought for early in Prohibition because of its shipping quality—it withstood the transcontinental journey better than most wine-grape varieties. Its high coloring-matter content also contributed to the eastern demand, since the color could be "stretched," that is, watered.

*Alicante Bouschet* is not recommended for California because of low quality and unstable coloring matter.

*Antibo*.—The Antibo is considered to be primarily a table grape in the Piedmont region of Italy, whence it came to California. At Davis it has been a fair producer, ripening somewhat irregularly, but usually in midseason. The clusters are only medium-sized. The berries are black and larger than the average. They have reached the crusher in good condition.

Though the musts have shown fair acidity from year to year at Davis, the pH has been relatively high. The dry wines have been flat, harsh, and very plain, with practically no aroma or bouquet and with only mildly vinous flavor.

Because of the almost complete lack of quality factors, little improvement could be secured by growing this variety in a cooler climate than region IV. It should be tested further for possible utilization in region IV for red sweet wine; and in region III and possibly II it might likewise be tried for table wine, though it does not appear promising. It should not be planted commercially in California.

*Aspiran noir*.—The Aspiran noir vines are fairly vigorous and productive. The clusters are large, conical, shouldered, compactly set with large, oval, firm berries. The fruit matures very late and at Davis, because of its large production, has not ripened properly. The grapes utilized were therefore immature; but, even so, their acid content was low. Because of deficiency in color, the fruit was pressed at once for white wines, which proved to be thin, light, and totally lacking in character.

Although the tests included only two lots, which were rather green, they definitely show that this variety is unworthy of a place in California.

(Text continued on page 640)

TABLE 21  
COMPOSITION OF MUSTS AND WINES OF RED VARIETIES WHICH ARE NOT RECOMMENDED

Region	Number of samples	Average harvest date, and year	Must			Wine			Tasting record
			Balling degrees	Total acid grams per 100 cc	pH	Alcohol, per cent	Fixed Extract, grams per 100 cc	Tannin, grams per 100 cc	
Alicante Bouschet									
I	2	Oct. 21, 1935	21.7	0.75	..	11.5	0.65	2.7	0.14
II	4	Oct. 7, 1935	20.6	0.60	..	10.6	.56	2.8	3YR-100
III	3	Oct. 1, 1935	20.8	0.50	..	10.2	.46	2.7	3YR-61
IV	4	Sept. 26, 1935	20.8	0.63	..	10.7	.44	2.5	3YR-60
V	3	Sept. 2, 1936	22.7	0.56	..	10.7	.40	2.9	3YR-27
I	1	Oct. 10, 1936	21.0	0.62	3.17	12.4	.75	3.1	3YR-29
II	0	Sept. 25, 1936	23.3	0.67	3.60	13.7	.54	3.2	-
III	3	Sept. 26, 1936	23.3	0.63	3.74	12.8	.48	3.2	VR-200
IV	13	Sept. 18, 1936	22.6	0.53	3.80	11.5	.47	3.2	3YR-51
V	7	Aug. 29, 1936	22.6	0.51	3.80	10.3	.43	2.7	3YR-43
I	1	Oct. 17, 1937	18.9	1.20	3.10	9.4	.88	2.8	1.170
II	1	Oct. 8, 1937	17.2	..	..	9.3	.76	2.7	3YR-25
III	1	Oct. 8, 1937	19.6	0.71	3.48	10.6	.47	2.4	333
IV	6	Oct. 6, 1937	20.0	0.70	3.61	10.7	.41	2.3	2R-23
I	1	Oct. 22, 1938	19.1	1.60	2.95	11.2	.93	2.7	2R-24
IV	3	Oct. 18, 1938	21.6	0.66	3.75	12.0	.49	2.9	3YR-39
IV	1	Sept. 28, 1939	21.1	0.43	3.42	11.6	.40	2.8	-
IV	1	Oct. 14, 1940	20.8	0.71	3.50	19.61	0.37	10.0	0.09
									...

\* For footnotes to table see page 639.

Antitho											
IV	1	Sept. 23, 1937	23.0	0.76	3.69	11.4	0.39	2.3	0.15	5VR-13	129
IV	1	Oct. 10, 1938	20.0	64	3.58	10.4	40	2.7	12	5VR-11	160
IV	1	Sept. 6, 1939	25.3	.61	3.33	12.1	.57	2.6	17	280	Fruity; full; harsh; about average quality
IV	1	Sept. 10, 1940	21.9	.66	3.55	11.4	.37	3.0	.12	222	Heavy and flat; very ordinary character
IV	1	Sept. 20, 1941	26.1	0.71	3.48	13.2	0.56	3.3	0.27	488	Heavy, intense color; average, slow-maturing
Asparan noir											
IV	1	Oct. 8, 1936	17.4	0.50	8.1	0.37	2.1	0.04	-	†	Some flavor; not delicate; ordinary
IV	1	Oct. 4, 1938	17.3	0.43	3.40	.	.	.	.	†	Neutral; very flat; poor quality
Black Hamburg											
I	1	Oct. 16, 1935	21.6	0.50	.	11.6	0.42	1.7	0.11	2R-7	Flat, no character; common
V	1	Oct. 21, 1935	23.4	.43	..	12.5	.36	2.5	0.06	2Ry-4	Flat, low acid; lacks color, flavor
I	1	Oct. 13, 1937	21.0	.44	3.44	11.9	.46	2.3	15	R-13	Flat, little flavor; ordinary quality
V	1	Oct. 2, 1937	20.6	31	3.63	12.1	.34	1.8	.05	†	Very flat; no flavor, very poor
I	1	Oct. 21, 1938	22.7	40	3.47	13.2	.50	2.4	20	3VR-29	Soft; undistinguished, medium color, common
V	1	Sept. 20, 1939	18.9	0.35	3.50	19.0†	0.32	1.9	0.03	83†	Soft, nutty sherry; gold color, average
Black Prince (Rose of Peru)											
I	1	Oct. 16, 1935	20.8	0.46	..	9.6	0.40	1.0	0.06	3RY-4	Soft pink wine, slightly distinct flavor; common
III	1	Oct. 2, 1935	23.3	40	..	11.8	.35	2.4	0.06	3RY-7	Flat, orange red, slightly gray, ordinary
IV	2	Oct. 1, 1935	23.7	39	..	11.5	.25	2.6	0.05	3RY-5	Orange-red color; very flat; poor fermentation
V	1	Sept. 4, 1935	25.4	48	.	11.6	.31	2.4	0.05	Y-4	Pink wine; very flat; slightly gray, poor
III	2	Sept. 22, 1936	27.5	43	3.94	18.7†	.34	12.8	0.05	3RY-8	Soft, tawny; slightly fruity, slightly gray
IV	3	Sept. 26, 1936	24.7	49	4.07	16.8†	.31	11.6	0.05	3RY-6	Soft, low color becoming brown, ordinary
V	1	AUG. 20, 1936	25.6	38	4.12	17.8†	.26	13.0	0.04	3RY-3	Becomes amber; shrivels with age
I	1	Oct. 4, 1939	23.6	54	3.40	17.7†	.30	13.4	0.01	.	Lacks color; soft fruity flavor; ordinary
V	1	Sept. 20, 1939	26.5	31	3.86	19.0†	.28	14.2	0.02	.	Angelica; very flat; ordinary
IV	1	Oct. 27, 1941	22.3	0.54	3.90	17.2†	0.30	12.6	0.04	...	Balanced Angelica; oxidizes; average

(Continued on following page)

TABLE 21—(Continued)

Region	Number of samples	Average harvest date, and year	Must			Wine			
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol per cent	Fixed acid, grams per 100 cc	Extract, grams per 100 cc	Color intensity*
Blane Elbe									
IV	1	Oct. 9, 1935	20.0	0.40	9.8	0.40	2.6	0.12	5VR-15
IV	1	Oct. 10, 1938	23.1	.55	3.63	12.6	.60	3.3	R-6
IV	1	Sept. 12, 1939	22.3	.70	3.22	10.7	.42	1.9	05
IV	1	Oct. 8, 1940	23.8	.50	3.55	13.2	.60	2.7	01
IV	1	Sept. 30, 1941	22.7	0.80	3.43	11.5	0.40	2.7	0.07
Bonarda									
IV	1	Oct. 18, 1938	24.8	0.55	3.55	13.5	0.43	3.0	0.24
IV	1	Sept. 8, 1939	23.5	.71	3.38	12.1	.72	2.9	27
IV	1	Sept. 4, 1940	23.6	.75	3.40	11.5	.39	2.7	19
IV	1	Sept. 25, 1941	26.7	0.68	3.41	13.7	0.57	3.5	0.30
Chauche noir									
II	1	Sept. 25, 1935	27.0	0.62	14.4	0.52	3.0	0.14	3VR-60
IV	1	Sept. 17, 1935	23.6	.45	10.7	.39	3.2	0.04	o.s §
II	1	Sept. 26, 1936	30.3	.41	3.75	20.0†	.36	12.5	18
IV	1	Sept. 13, 1936	26.0	.47	4.00	20.3†	.33	12.2	06
II	1	Sept. 22, 1937	23.2	.76	3.44	12.0	.60	2.7	17
IV	1	Aug. 20, 1940	24.0	0.66	3.42	20.7†	0.33	11.1	0.02

Chenin noir											
IV	1	Sept. 21, 1938	20.2	0.41	3.43	10.3	0.45	2.6	0.11		Neutral; little character, somewhat flat
IV	1	Sept. 6, 1939	21.9	.57	3.40	10.7	.49	2.2	.03	43	Neutral, slight flavor, fair balance; pleasant
IV	1	Aug. 29, 1940	23.1	.65	3.50	12.0	.35	2.5	.06	52	Fruity flavor; mild, flat, common
IV	1	Sept. 30, 1941	26.5	0.65	3.68	13.9	0.46	3.1	0.10	58	Flat, alcoholic; not pleasing, poor quality
Coristano											
IV	1	Oct. 9, 1935	23.0	0.65	8.8	0.46	2.6	0.03			Distinct; little flavor; thin, flat, poor
IV	1	Oct. 17, 1936	16.6	.51	3.61	8.5	.32				Thin, not balanced, very poor, tends to spoil
IV	1	Oct. 31, 1938	19.0	.66	3.99	10.4	.54	2.6	.04	10†	Tart; fruity, light, little character, common
IV	1	Oct. 17, 1939	20.2	.56	3.40	11.2	.60	2.7	.04	18†	Common flavor, rather lifeless, heavy, ordinary
IV	1	Oct. 28, 1940	18.1	.56	3.60	10.1	.38	2.5	.03	14†	Thin; flat; characterless; very poor
IV	1	Oct. 24, 1941	18.0	0.71	3.33	9.7	0.56	2.1	0.04	84†	Thin, earthy, not balanced, poor
Criolla Mesa and Criolla Vino											
IV	2	Oct. 17, 1938	23.7	0.49	3.63	13.5	0.47	2.8	0.10	3Ry-5	67
IV	2	Oct. 10, 1939	25.3	.42	3.68	21.7†	.28	10.5	.03		81
IV	2	Oct. 28, 1940	26.3	.44	3.84	21.2†	.29	9.1	.07		308
IV	2	Nov. 4, 1941	24.6	0.48	3.68	21.1†	0.46	4.1	0.04		20†
Croatto Moretto											
IV	1	Oct. 8, 1935	22.2	0.63	10.8	0.36	2.5	0.07			Very common flavor, lacks color, no character
IV	2	Sept. 22, 1936	21.0	.55	4.00	10.8	.49	2.8	.17	417	Oxidized color, flavor, tends to spoil
V	1	Aug. 26, 1936	18.5	.68	4.02	0.6	.30	2.8	.19	290	Slight flavor, flat; tends to spoil, poor
IV	1	Sept. 14, 1937	22.3	.72	3.98	10.8	.37	2.8	.19	250	Below average quality; little distinction; harsh
V	1	Sept. 24, 1937	21.2	0.47	3.98	10.0	0.37	2.5	0.15	250	Mediocre quality; not balanced; flat

(Continued on following page)

TABLE 21—(Continued)

Region	Number of samples	Must				Wine			
		Average harvest date, and year	Total acid, grams per 100 cc	pH	Alcohol per cent	Fixed acids, grams per 100 cc	Extract, Tannin, grams per 100 cc	Color intensity*	Tasting record
<i>Croatto Moretto—(Continued)</i>									
IV	1	Oct. 10, 1938	23.1	0.51	3.74	11.7	0.42	2.9	0.15
IV	1	Aug. 31, 1939	22.0	73	3.26	10.3	49	2.4	13
V	1	Aug. 30, 1939	18.5	60	3.38	10.4	58	1.8	20
IV	1	Aug. 28, 1940	22.0	73	3.43	10.2	41	2.6	16
IV	1	Sept. 30, 1941	25.4	0.67	3.50	12.9	0.56	3.4	0.17
<i>Doleotto</i>									
IV	1	Oct. 7, 1937	26.0	0.51	3.76	15.1	0.52	0.17	1VR-18
IV	1	Oct. 10, 1938	22.1	37	3.71	13.2	36	2.8	14
IV	1	Sept. 12, 1939	22.9	55	3.41	11.6	54	2.7	10
IV	1	Sept. 16, 1940	24.3	60	3.63	18.2†	41	8.2	17
IV	1	Sept. 23, 1941	23.6	0.66	3.42	12.2	0.49	2.7	0.15
<i>Early Burgundy</i>									
II	3	Sept. 22, 1939	23.4	0.64	3.40	12.6	0.45	2.7	0.15
II	2	Sept. 19, 1940	21.8	57	3.50	11.5	49	2.9	16
II	2	Sept. 17, 1941	21.5	0.70	3.38	11.3	0.49	2.7	0.15

Grand noir											
II	3	Oct. 4, 1935	20.0	0.53	9.8	0.55	2.4	0.06	3VR-22	-	Slightly aromatic; rough, thin
III	2	Oct. 3, 1935	20.8	0.53	9.5	0.59	2.5	0.16	3VR-66	R-23	Thin; little flavor; picked too early
IV	2	Sept. 18, 1935	21.1	64	10.5	46	2.5	0.15	-	-	Little character; slightly harsh; color unstable
II	4	Oct. 9, 1936	21.5	.51	4.00	12.9	49	4.3	VR-20	333	Distinctly aromatic; rather harsh; common
III	2	Sept. 22, 1936	21.8	.47	3.78	12.1	45	3.1	VR-30	520	Slightly aromatic; bitter; ordinary aftertaste
I	1	Oct. 21, 1937	18.4	63	3.32	10.5	50	2.6	3VR-31	356	Very aromatic; rough; common
II	1	Oct. 20, 1937	20.4	50	3.64	10.8	34	2.5	1R-5	167	Aromatic; flat; ordinary
III	1	Oct. 4, 1938	22.3	.42	3.38	11.7	38	2.2	-	-	Rough; lacks character; flat; mediocre
IV	1	Sept. 28, 1939	23.2	.46	3.70	19.1†	43	8.1	07	250	Ordinary red dessert wine; good color
IV	1	Oct. 14, 1940	25.6	.57	3.85	20.4†	33	11.4	-	340	Very aromatic; common dessert quality
IV	1	Oct. 20, 1941	24.7	0.53	3.60	18.7†	0.36	14.7	0.13	426	Typical, undesirable aromas; ordinary
										414	
Grec rouge											
IV	1	Oct. 8, 1935	17.4	0.56	8.5	0.33	2.2	0.05	-	-	Very thin; little character, flat
IV	1	Oct. 10, 1938	21.1	.44	3.74	11.6	46	2.3	03	-	† Little flavor, flat, poor quality
IV	1	Sept. 12, 1939	22.2	.51	3.45	11.2	32	1.8	01	16	Very flat, no character or quality
IV	1	Oct. 8, 1940	22.5	.47	3.73	12.4	48	2.4	02	25	Little flavor; flat; very poor quality
IV	1	Sept. 30, 1941	25.9	0.64	3.40	13.5	0.48	2.5	0.06	-	Flat; unpromising flavor; ordinary
										9	
Grosse blane											
IV	1	Sept. 8, 1938	21.2	0.68	10.2	0.52	2.9	0.17	3VR-20	222	Oxidized, ordinary quality
IV	1	Sept. 6, 1939	22.6	.87	3.25	11.2	45	2.7	-	173	Average flavor, flat, below average
IV	1	Sept. 10, 1940	20.7	.81	3.50	11.2	45	2.6	.12	164	Fruity; oxidized; little character
IV	1	Sept. 26, 1941	23.7	0.84	3.40	12.9	0.48	2.7	0.10	186	Lacks distinct flavor; flat; mediocre

(Continued on following page)

TABLE 21.—(Continued)

Region	Number of samples	Average harvest date and year	Must				Wine				Tasting record
			Balling degrees	Total acids, grains per 100 cc	pH	Alcohol per cent	Fixed acids, grams per 100 cc	Extract, Tannin grams per 100 cc	Tannin grams per 100 cc	Color intensity*	
Kadarika											
IV	1	Sept. 23, 1935	19.9	0.41	-	10.1	0.37	2.1	0.13	3R-8	Low color, flavor; alcohol, flat, unstable
IV	1	Sept. 13, 1936	20.8	.33	3.56	10.6	30	2.5	0.09	3R-7	Very flat; lacks flavor, poor
IV	1	Oct. 17, 1938	22.2	.46	3.70	12.3	.33	2.5	0.12	3R-4	Flat; tasteless, very poor quality
IV	1	Sept. 12, 1939	21.2	.50	3.61	10.0	37	2.5	0.05	3Ry-3	Orange-pink color; slightly fruity; flat, not balanced
IV	1	Oct. 8, 1940	24.5	.51	3.85	†	29	15.4	0.12	-	Deficient, undesirable color, very flat; soft
IV	1	Oct. 24, 1941	20.4	0.52	3.86	20.7†	0.32	13.3	0.07	-	Soft; slightly fruity; too low in color
Kopetcha											
IV	1	Aug. 12, 1939	22.1	0.71	3.40	9.7	0.47	2.3	0.11	-	245
IV	1	Aug. 19, 1940	22.9	1.06	3.38	11.8	.46	2.7	0.12	-	Fruity, distinct flavor; light; pleasant
IV	1	Sept. 26, 1941	27.3	0.50	3.69	14.3	0.61	3.6	0.22	-	163
Lambrusche Langhe											
V	1	Aug. 23, 1935	20.1	0.98	-	8.9	0.63	2.7	0.11	6VR-44	Orangered color; distinct, fruity; tart; thin
V	1	Aug. 26, 1936	18.5	.68	3.85	9.3	66	2.8	1.1	-	Distinct flavor; good acid, thin, low color, alcohol
V	1	Sept. 4, 1937	18.2	.56	3.58	8.7	55	2.5	0.08	-	Distinct character, thin, not balanced; ordinary
V	1	Aug. 30, 1939	19.3	0.55	3.49	7.6	0.48	2.4	0.13	3Ry-6	Oxidized, thin, slightly flat; common

Lenoir												
									3RY-12	126		
IV	1	Sept. 13, 1936	24.0	0.33	3.75	11.8	0.40	-	-	-	Distinct American flavor; fair balance, but flat	
I	1	Oct. 4, 1939	23.9	0.60	3.42	12.3	.59	2.9	0.14	833	Common varietal flavor, very plain, intense red	
I	1	Sept. 24, 1940	22.8	1.20	3.22	12.1	0.71	3.2	0.20	540	Distinct American flavor; rough; harsh; tart	
Macaroli												
IV	1	Oct. 8, 1935	16.9	0.66	..	7.9	0.63	2.0	0.02	-	Tart; little flavor; thin; poor	
IV	1	Oct. 17, 1937	17.1	60	3.30	8.1	.52	-	-	-	Tart; no flavor, thin, methocro	
IV	1	Oct. 31, 1938	14.2	75	3.83	8.2	.57	1.9	.03	32	Fresh, little character; ordinary quality	
IV	1	Oct. 9, 1939	22.8	67	3.30	11.5	.45	2.2	.08	66	No character or flavor; flat, very ordinary	
IV	1	Oct. 8, 1940	21.4	66	3.45	12.3	.57	3.5	.03	12	Tart; little flavor, but no character	
IV	1	Oct. 29, 1941	18.3	0.82	3.11	9.9	0.66	2.2	0.05	15	Tart; thin; little character; very common	
Marzemino												
IV	1	Sept. 23, 1935	20.8	0.41	9.1	0.43	2.5	0.15	1YR-44	-	Rather fruity, distinct, thin; flat; average	
IV	1	Sept. 26, 1937	20.8	53	3.75	10.7	.52	2.8	.14	3YR-17	222	Distinct aroma, fruity; good flavor, above average
IV	1	Oct. 3, 1938	21.9	41	3.73	12.2	.42	3.6	.14	3YR-27	286	Good color, flat; oxidized, ordinary quality
IV	1	Oct. 2, 1939	24.0	.39	3.80	12.4	.32	3.0	.11	-	222	Very flat; little character or quality
IV	1	Sept. 26, 1941	24.2	0.65	3.71	12.3	0.56	3.2	0.36	910	Common, flat, coarse; high color	
Mataro												
I	2	Oct. 21, 1935	24.3	0.84	-	11.2	0.73	2.9	0.13	3YR-27	Slightly distinct aroma; balanced, undistinct, crushed	
II	2	Oct. 9, 1936	21.2	.63	-	11.1	.52	2.5	.09	3YR-27	Sound, little character, but palatable, average quality	
III	2	Oct. 10, 1936	19.5	.60	10.1	10.1	.51	2.3	.07	5YR-16	Light in color and flavor, thin	
IV	2	Oct. 1, 1936	23.8	.52	11.3	.37	2.1	.05	2YR-5	Oxidized, deficient in color; flat; poor		
V	1	Sept. 11, 1935	22.4	0.45	-	11.4	0.41	2.5	0.06	3YR-6	Low color and acid, very poor	

(Continued on following page)

TABLE 21—(Continued)

Region	Number of samples	Average harvest date, and year	Must		Wine				Tasting record
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol, per cent	Fixed Extract, acid, grams per 100 cc	Tannin, grams per 100 cc	
Matero—(Continued)									
I	3	Oct. 4, 1936	22.1	0.65	3.74	12.9	0.55	3.1	0.16
II	2	Oct. 6, 1936	20.9	0.47	3.68	10.8	0.38	2.3	3R-8
III	4	Sept. 28, 1936	21.0	0.46	3.89	17.7†	0.37	11.6	3Ry-3
IV	3	Sept. 14, 1936	23.6	0.43	3.64	13.2	0.37	2.9	3R-7
V	1	Aug. 30, 1936	21.0	0.46	4.10	16.3†	0.34	7.4	0.08
I	2	Oct. 15, 1937	18.9	0.85	3.25	11.1	.55	2.4	.12
II	2	Oct. 19, 1937	21.5	0.68	3.64	11.3	.39	2.7	R-15
III	2	Oct. 3, 1937	20.8	0.66	3.42	11.6	.49	2.3	VR-10
IV	1	Oct. 2, 1937	20.1	0.70	3.54	15.7†	.41	9.7	3YR-13
V	1	Oct. 12, 1937	23.4	0.59	3.84	19.9†	0.25	11.3	0.06
I	1	Oct. 23, 1938	18.7	1.63	3.03	12.5	.89	2.7	2R-6
II	1	Oct. 22, 1938	21.5	1.02	3.12	11.1	.70	2.5	3R-10
IV	1	Sept. 31, 1938	22.6	0.51	3.77	12.3	.42	3.0	.11
I	3	Oct. 6, 1939	20.9	0.88	3.03	10.9	.68	2.6	R-25
II	4	Sept. 22, 1939	20.9	0.67	3.17	10.7	.69	2.0	3R-50
IV	1	Sept. 28, 1939	20.0	0.64	3.45	17.5†	.49	5.4	194
I	3	Oct. 9, 1940	18.7	1.15	3.00	9.4	.65	2.3	3R-6
II	3	Sept. 6, 1940	21.0	0.69	3.41	10.6	.57	2.6	193
IV	2	Oct. 6, 1940	24.9	0.63	3.60	19.3†	.39	12.1	195
I	2	Oct. 4, 1941	20.8	0.48	3.02	10.4	.71	2.2	60
II	2	Oct. 1, 1941	22.4	0.82	3.09	12.5	.70	2.6	179
IV	1	Oct. 26, 1941	23.9	0.80	3.49	19.5†	.40	14.5	180
									162
									190
									164
									97

Distinct; balanced, fair tawny dessert wine  
 Low color, some flavor, flat; ordinary table, dessert wines  
 Ordinary pink dessert wine; poor table wine  
 Coarse; oxidized, poor. Dessert wines of duplicate lots also  
 poor  
 Low-quality red sweet wine  
 Slightly distinct; flavor, standard quality  
 Typical flavor; flat; tends to spoil; common  
 Lacks character; fair pink from duplicate sample  
 Brown-red; average quality dessert wine  
 Slightly oxidized, low color; average quality  
 Very tart, fruity; distinct flavor; blending quality  
 Distinct flavor; early-maturing, average quality  
 Oxidized, flat; unpromising; low quality  
 Typical flavor; tart; balanced; average  
 Light flavor, color; fruity; ordinary  
 Very deficient in color; poor quality  
 Fruity; very thin; lacks color; picked too early  
 Thin; slightly distinct flavor; average quality  
 Coarse; ordinary-quality red table wine  
 Thin, distinct, undesirable flavor; unripe grapes  
 No particular character; average quality  
 Average-quality red dessert wine; deficient color

Meunier											
		Oct.	16, 1935	18.6	0.90	-	9.1	0.43	2.3	0.09	3VR-19
I	1	Aug. 31, 1938	22.4	.71	3.61	11.9	.46	2.5	.15	3VR-28	Soft; thin; oxidizes easily; ordinary
IV	1	Aug. 16, 1938	22.3	.64	3.30	10.7	.36	2.4	.08	-	Slightly distinct flavor; average (acid reduction)
IV	2	Aug. 17, 1940	22.8	.61	3.43	11.9	.39	2.5	.08	.....	Distinct flavor; fruity; pleasant; lacks acid
IV	2	Aug. 23, 1941	21.5	0.73	3.35	10.9	0.46	2.8	0.13	.....	Very flat; slightly distinct aroma; ordinary
											Flat; pink; rich; only slightly distinct aroma
Negro Amaro											
IV	1	Sept. 13, 1936	19.9	0.73	3.06	10.4	0.58	3R-4	68	Fair balance; lacks flavor, color	
IV	1	Oct. 15, 1937	23.8	0.89	3.49	12.4	.46	3.1	0.09	R-7	71
IV	1	Oct. 3, 1938	22.9	0.77	3.51	11.7	.70	3.5	12	R-11	112
IV	1	Sept. 12, 1939	23.7	1.07	3.15	11.6	.69	3.1	.08	.....	Fruity; medium distinct aroma; rich; soft
IV	1	Sept. 17, 1940	22.7	1.05	3.26	11.4	.43	2.9	.03	.....	Fruity flavor; soft, harmonious; average
IV	1	Oct. 1, 1941	23.9	1.13	3.25	12.0	0.63	3.0	0.10	.....	Tart; fair flavor; average quality
											Naretta
IV	1	Oct. 9, 1936	21.7	0.64	4.04	11.1	0.56	3R-17	220	Shightly fruity; fair balance; ordinary quality	
IV	1	Sept. 23, 1937	22.3	.68	3.87	11.0	.44	2.4	0.11	3VR-14	142
IV	1	Oct. 10, 1938	20.4	.50	3.87	10.1	.45	2.8	10	R-11	93
IV	1	Aug. 30, 1939	23.6	.77	3.25	11.2	.44	3.0	.21	.....	Practically neutral; flat; common
IV	1	Sept. 4, 1940	24.2	.58	3.55	12.1	.40	2.6	12	.....	Slight flavor, lacks freshness; heavy; rough
IV	1	Sept. 20, 1941	26.2	0.58	3.70	13.0	0.46	3.3	0.20	.....	Almost neutral; ordinary quality
											Coarse; common; flat, not very promising

(Continued on following page)

TABLE 21—(Continued)

Region	Number of samples	Average harvest date, and year	Must			Wine			Tasting record
			Balling degrees	Total solid grams per 100 cc	pH	Alcohol, per cent per 100 cc	Fixed acid, grams per 100 cc	Tannin, grams per 100 cc	
I	1	Oct. 16, 1935	21.6	0.58	11.0	0.54	2.5	0.24	2VR-100
IV	1	Sept. 23, 1935	18.9	.47	9.7	.41	2.3	.09	3VR-20
V	2	Aug. 30, 1935	19.7	.57	8.6	.33	2.8	.22	4VR-42
IV	2	Sept. 22, 1936	21.7	.33	3.91	11.5	.40	3.3	4VR-36
V	1	Aug. 26, 1936	20.3	.37	3.62	10.3	.46	3.1	24
IV	2	Sept. 24, 1937	19.3	.53	3.91	10.2	.43	2.6	15
V	1	Sept. 24, 1937	20.6	.42	3.90	9.8	.38	2.8	15
IV	1	Oct. 10, 1938	24.3	.49	3.93	12.3	.45	3.3	15
IV	1	Sept. 12, 1939	22.9	.51	3.50	10.5	.44	3.1	21
IV	1	Oct. 8, 1940	24.1	.36	4.00	15.7†	.42	9.2	22
IV	1	Oct. 27, 1941	25.0	0.40	4.11	21.1†	0.33	7.8	0.13
Pagefortito									
I	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Fuisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Suisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Fuisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Suisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Suisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Suisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Suisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Suisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Suisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Suisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Suisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Suisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Suisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50	3.69	11.3	0.57	2.8	0.15
Pouilly Suisse									
II	1	Oct. 1, 1935	24.5	0.82	12.6	0.46	2.7	0.25	4VR-50
III	1	Oct. 7, 1935	20.8	.50	10.9	.37	2.3	14	5VR-31
IV	1	Oct. 3, 1935	19.5	.60	9.6	.38	2.4	15	3R-8
V	1	Sept. 4, 1935	23.0	.58	12.7	.44	2.7	15	R-22
II	1	Oct. 1, 1936	21.8	.54	4.07	12.3	.44	2.8	22
IV	1	Oct. 2, 1937	24.4	.78	3.92	20.4†	.48	5.2	13
V	1	Oct. 3, 1938	22.1	0.50					

IV	1	Sept 25, 1939	26.0	0.51	3.50	20.91	0.47	11.4	0.09		300	Slightly aromatic, astrangent, ordinary quality
IV	1	Oct. 15, 1940	27.5	4.01	20.11	43	10.6	13			714	Slightly aromatic, alcoholic, below average
IV	1	Oct. 22, 1941	27.9	0.56	3.69	10.91	0.47	14.8	0.20		869	Harsh; distinct, undesirable aroma; average
						Petite Verdot						
I	1	Oct. 16, 1935	23.5	0.70	12.0	0.50	3.4	0.12	3VR-31		Fresh, slightly rough, some character	
IV	2	Sept. 20, 1935	23.1	.83	10.5	.63	2.7	.17	3VR-36		Slightly distinct flavor, thin, soft, common	
IV	1	Sept. 13, 1936	22.6	46	3.54	11.1	50	3.0	14	5VR-31		
IV	1	Sept. 26, 1937	22.8	60	3.52	11.0	.33	2.5	17	4VR-19		
IV	1	Sept. 4, 1940	23.6	53	3.40	10.5	48	3.2	16		222	
IV	1	Sept. 10, 1941	24.2	0.50	3.30	11.7	0.52	3.1	0.20		351	
						Pfeffer						
I	1	Oct. 10, 1936	22.4	0.66	3.80	12.6	0.56	2.5	0.10	3VR-21		285
I	2	Oct. 17, 1937	18.5	1.00	3.24	9.4	.07	2.5	R-10		100	
I	1	Oct. 22, 1938	20.0	1.30	2.88	10.5	.70	2.3	15	R-18		
I	3	Oct. 4, 1939	20.3	0.90	2.92	10.2	.75	2.5	11		77	
III	1	Sept. 22, 1939	24.2	0.78	3.15	13.4	.63	2.8	.07		124	
I	2	Oct. 13, 1940	20.1	1.22	2.99	10.0	.68	2.6	.07		245	
I	2	Oct. 5, 1941	21.4	1.36	2.89	10.0	0.69	2.7	0.17		119	
						Pipoule noir						
IV	1	Oct. 9, 1935	19.7	0.80	9.8	0.42	2.4	0.06			132	
IV	2	Oct. 7, 1938	20.9	.56	3.35	11.3	.63	2.5	.07	3R-5		
IV	1	Sept. 12, 1939	21.8	.85	3.15	11.2	.61	2.6	.03		25	
IV	1	Oct. 1, 1940	24.2	.71	3.50	13.6	.65	2.7	.09		155	
IV	1	Oct. 22, 1941	22.3	0.71	3.19	12.0	0.58	2.7	0.08		51	
											47	
											Thin but pleasant; pink; fruity; little character	

(Continued on following page)

TABLE 21—(Concluded)

Region	Number of samples	Average harvest date, and year	Must				Wine			
			Total acid, grams per 100 cc	Balling degrees	pH	Alcohol, per cent	Fried acid, grams per 100 cc	Extract, Tannin, grams per 100 cc	Tannin, grams per 100 cc	Color intensity*
Pinot Fernand										
IV	1	Sept. 17, 1936	24.2	0.78	-	11.3	0.35	2.9	0.07	31Y-8
I	1	Sept. 10, 1936	25.8	.52	3.61	14.7	47	3.3	12	5YR-20
IV	1	Aug. 31, 1936	23.9	.54	3.71	11.0	54	3.0	07	o.s.¶
IV	1	Aug. 31, 1938	22.0	70	3.53	11.3	40	2.8	15	Oxidized; slight varietal flavor, flat.
IV	1	Aug. 12, 1939	20.2	.83	3.31	8.6	40	2.4	07	-
IV	1	Aug. 19, 1940	22.4	.89	3.40	10.8	.36	2.6	05	-
III	1	Aug. 26, 1941	22.2	1.11	3.34	11.0	0.41	2.8	0.13	43
										Little color, flat, distinct varietal aroma; ordinary.
										Oxidized; distinct aroma, fair color
Pinot Saint George										
III	1	Oct. 7, 1936	25.3	-	11.8	0.37	2.7	0.10	5YR-22	190
IV	2	Sept. 20, 1935	21.1	0.77	..	9.9	.53	2.7	0.10	2R-14
III	1	Sept. 28, 1936	27.6	34	4.05	13.4	40	2.9	-	155
IV	1	Sept. 13, 1936	23.4	42	3.80	11.1	39	2.0	061	Some aroma; fruity; ordinary.
I	1	Oct. 13, 1937	25.0	.59	3.89	14.3	.50	3.1	16	3YR-22
IV	2	Sept. 8, 1937	22.7	.74	3.61	10.8	.65	2.2	11	2R-11
III	1	Sept. 21, 1938	22.3	.44	3.40	12.8	.50	3.0	19	3YR-25
IV	4	Sept. 26, 1938	22.1	0.55	3.84	11.5	0.48	3.0	0.11	R-12
										Light flavor; rough; heavy; ordinary.
										Light flavor; rough; flat; and common
										Raisin flavor; rough; heavy; ordinary.
										Some flavor; distinct; fair balance, average.
										Fruity; some character; balanced.
										Fruity; medium distinct; somewhat flat

I	1	Oct. 4, 1939	20.5	0.63	3.31	12.0	0.39	2.1	0.10	...	...	166
III	2	Sept. 12, 1939	24.7	.48	3.35	13.4	.46	2.3	.07	...	...	425
IV	3	Sept. 16, 1939	22.4	63	3.63	11.4	44	2.7	.08	...	...	227
I	1	Sept. 4, 1940	23.2	.47	3.45	11.8	.41	2.4	.12	...	...	154
III	1	Sept. 4, 1940	24.1	.53	3.54	12.7	.39	2.6	.12	...	...	150
IV	4	Sept. 7, 1940	20.7	.75	3.63	11.4	.46	2.6	.03	...	...	351
II	1	Oct. 7, 1941	25.0	.60	3.60	13.2	.50	2.9	.22	...	...	400
IV	4	Sept. 28, 1941	22.7	0.85	3.60	11.3	0.48	3.0	0.08	...	...	1061

## Tinta amarela

IV	1	Sept. 23, 1935	17.7	0.61	8.6	0.36	1.8	0.06	R-6	...	...	...
IV	1	Sept. 13, 1936	19.3	63	3.82	19.0†	.44	7.1	.05	2R-7	...	128
IV	3	Oct. 7, 1936	18.5	.56	3.51	18.2†	.53	7.8	.07	2RY-14	...	161
IV	2	Sept. 28, 1939	21.7	.75	3.32	18.0†	.52	9.6	.03	...	...	137
IV	1	Oct. 24, 1941	23.0	0.72	3.63	12.1	0.60	3.3	0.07	...	...	120

\* Data in left column, by the Duquardin-Salleron vine-colorimeter, following Hilgard's procedure; the observed figures have been divided into 4,000 so that the recorded figures will be proportional to intensity. Data in right column, by use of color standards and a color comparator.

† Fermentation arrested by the addition of grape brandy.

‡ Pressed immediately after crushing and fermented off the skins.

§ Color too light to measure.

¶ Unusually low because of overtopping and a very cool season.

*Black Hamburg.*—The Black Hamburg is the Englishman's ideal table grape. But like the principal table grape of France, the Chasselas doré, it has not made a place for itself in California, since it will not carry to the distant markets and still be attractive to the consumer.

The vines are very vigorous and productive. The clusters are very large, long-conical, winged, and well filled with large, round, crisp, juicy berries. The peduncle is long. The grapes are easily crushed, and the juice yield is large. Ordinarily the grapes mature in excellent condition.

The figures of table 21 definitely show that the musts of Black Hamburg, regardless of locale, are poorly suited for table wines. Although none of the lots were very mature, the highest total acidity was 0.50 per cent. This was in a sample from Bonny Doon, which is among the coolest areas where grapes are now being grown in California.

The common fault of Black Hamburg table wines has been flatness and lack of freshness. In addition, they have had little if any flavor. In no case were there indications of distinctiveness. When fermented on the skins the product contains approximately enough color for normal pink or *rosé* wines.

The sherry sample was soft, of pleasing flavor and color, but only of average quality. The variety is, without question, much better adapted for dessert than for table wines. However, the observations indicate it to be much inferior to the Mission and Grenache for this purpose.

Black Hamburg is not recommended for wine production in California.

*Black Prince (Rose of Peru).*<sup>60</sup>—The Black Prince has been grown to some extent in California. In many old plantings of Flame Tokay and Mission it occurs as an occasional mix. The variety grows vigorously and, with not-too-short spur pruning, will produce large yields. In the past it has been grown almost exclusively for table use; the crisp, juicy texture and mild, spicy flavor appeal to most consumers. The vine is not too resistant to mildew.

The clusters are large, conical, shouldered, and usually well filled to compactly set with large, round, firm, reddish-black berries. The veins beneath the skin are usually visible at maturity.

As with all other good table grapes, the must is too low in acid for a balanced table wine. Generally the product was flat, almost without color, lacking in character, and unbalanced, with only a slight grape flavor. Not one of the table wines rated above ordinary.

Judging from the composition of its must, this variety may be well suited for dessert wines. This view is supported somewhat by the red sweet wines of region III—soft, slightly fruity, with some grape flavor and a tawny color. The other red sweet wines, however, have been unbalanced, very deficient in color, and apt to oxidize or sherrify at an early age. The Angelica lot was pleasing, soft, and mellow, but too flat.

The tests definitely indicate that the Black Prince is surpassed by many varieties for both table and dessert wines. It should not be planted in California for wine production. Present plantings could more profitably be employed for table purposes. If delivered to the winery the grapes should be

<sup>60</sup> This is not the Black Prince of Europe, known also as the Trollinger, Frankenthaler, and Black Hamburg. The use of the name Rose of Peru may be questioned as well; hence the variety is listed under the name most common in California.

pressed immediately, and the white must used for Angelica, sherry, or distilling material.

*Blaue Elbe*.—The vines of the Blaue Elbe are vigorous, hardy, and very productive. The clusters are large and are usually well filled with large-medium, round, reddish-blue berries. The tender skin renders the fruit subject to handling injuries and to damage by early rains.

At Davis the Blaue Elbe was too deficient in acidity and color to produce normally balanced red table wines. The wines were flabby and only orange red; they possessed but little flavor and no character; and without acidification their quality was relatively low.

This variety has made a very poor showing in region IV. The character of its fruit and the considerable summation of heat required to mature it indicate that it will not be adapted in cooler regions. It should not be planted in California.

*Bonarda*.—The Bonarda is reported to be one of the strong-growing productive sorts of northwestern Italy. Its clusters are medium-sized, conico-cylindrical, well filled with medium-sized, round, late-maturing berries. At Davis it has proved only a moderate producer.

Its musts have been only relatively well balanced for dry table wines in region IV, the pH being rather high. The wines have been heavy, astringent, of limited character, with only slight though pleasing aroma. They age slowly and keep only moderately well.

These tests, together with Hilgard's,<sup>a</sup> definitely show that Bonarda is not a satisfactory producer of dry table wines in the regions from which it has been collected. It does not merit further tests.

*Chauche noir*.—This variety has small clusters and berries. It ripens early. Since the foliage is not dense, it raisins easily. The grapes are difficult to crush, and the juice yield is very poor in warm seasons. Its production is below average.

Hilgard found the variety to resemble the Pinot in several respects but to lack the requisite composition and character for red table wines. This observation is confirmed by the present studies. The musts were excessively sweet and lacked acid. The table wines were flat, easily oxidized, and completely unsatisfactory. The dessert wines have had too much raisin flavor and lacked color; otherwise they were not undesirable and somewhat resembled those of Trouseau. The variety is accordingly not recommended for California.

*Chenin noir*.—The Chenin noir has large, rather tight clusters. In humid regions this feature would probably be a disadvantage, but at Davis the grapes have reached the winery in good condition. Ripening is about midseason.

The grapes from region IV have produced poor table wines—plain, almost without aroma or character, unbalanced, and flat. Very ordinary would be an appropriate designation. The coloring is low, suitable only for pink wines.

This variety did not reveal sufficient quality or character in region IV to justify further testing in cooler regions, where color and acidity would be higher. The lack of flavor and the large tight clusters are the primary objections. It is not recommended.

*Coristano*.—The Coristano is a rather vigorous grower and a heavy pro-

<sup>a</sup> See citations in footnote 15, p. 496, and footnote 16, p. 496.

ducer. Its clusters are large, long-conical, and well set with medium-sized, firm berries. It matures very late. The low-sugar musts were of only moderate acidity and above-average pH.

The wines from region IV were in general unsatisfactory, having little flavor or character, and were unbalanced and deficient in acid. Not one lot merited a quality rating above ordinary.

This variety is not adapted to regions IV and V. In IV its fruit did not reach normal maturity, and still its acidity was low. In V it would mature fully, but the product would be too flat. Since it will not mature in regions cooler than Davis, further testing is unnecessary. The variety is not recommended.

*Criolla Mesa and Criolla Vina*.—These varieties came to California from Latin America, where they have been grown since the Colonial period. They closely resemble the Mission in their vegetative characters, vigor of growth, and cluster size, shape, and density. The same is true of the berries of the Criolla Vina, but those of the Criolla Mesa are half again larger than Mission. Also like Mission the grapes ripen late and remain in good condition. Their juice yield is only fair if pressed off immediately after crushing, as the fruit is rather fleshy and thick-skinned.

The dry table wines were complete failures—poorly balanced, with little aroma, flavor, or character. They were difficult to age or store, duplicating in this respect the experience with Mission.

The dessert wines, though much better, in no respect surpass the same types produced from Mission. They approach the quality of the Mission wines. Low color content prevents their use for red dessert wines by themselves; they must be blended or pressed off white for Angelica or sherry material. On the basis of these tests in region IV, neither variety can be recommended; the Mission is to be preferred.

*Croetto Moretto*.—The Croetto Moretto grows vigorously and produces large crops. The vines leaf out relatively late and resist mildew. The clusters are medium-sized, cylindrical, winged, and rather compactly set with medium-large, round, black berries. Because of the thick skin and firm texture, the fruit reaches the crusher in good condition. Late in the season, however, it shatters badly, and many berries may be lost in transport.

The table wines from regions IV and V have been unsatisfactory—almost neutral in aroma and flavor, low in acidity, only fair in balance, and poor to ordinary in quality. A number have spoiled, a tendency not surprising in view of the high pH of the musts.

This variety has failed badly in the location where it has been grown and should not be planted anywhere in the state. The statement checks with Hilgard's experience and with Bioletti's failure to mention the variety.

*Dolcetto*.—The Dolcetto came to us from northern Italy, where, according to Hilgard,<sup>62</sup> it has been prized for its early maturing and good coloring. In California it has ripened about midseason, although in two years the alcohol yield indicates the presence of dried fruit in the clusters at crushing. Its wines here have shown only an average amount of color. The variety is vigorous and above average in productivity.

The clusters are large, conical, winged, and well filled with round, thin-

<sup>62</sup> See citation in footnote 16, p. 496.

skinned berries. The fruit is not very resistant to handling injuries. The grapes are easily crushed, and the juice yield is good.

In region IV the wines have been regularly deficient in acid. They have varied from rough to soft, from heavy to light, and none have shown a marked or distinctive aroma or flavor. A rating of common dry table wines is all they merit. The variability in their character largely results from difficulty in harvesting them before raisining sets in.

The variety does not fit into California conditions. In regions IV and V it lacks acidity, while in the cooler regions it will not show enough character to compete with equally productive varieties of higher quality.

*Early Burgundy*.—The correct name for this variety has not been discovered. It resembles the Pinot noir in its composition, but not in its vine characteristics. The clusters are medium-large; the berries above average in size. On the floor of the Napa Valley it is a good producer. The fruit is well protected by foliage and if picked in September reaches the crusher in good condition. The juice yield is good.

The musts from region II are of only moderate acidity. The wines have been uniformly deficient in acid even though harvesting was in mid-September; they have had a soft flavor, but not outstanding. Because of its low acid and undistinguished flavor the variety is not adapted to the production of red table wines of the Burgundy-type in California. It might possibly be of better composition in region I, but the flavor is not sufficiently distinctive to warrant plantings. The variety should not be planted further.

*Grand noir*.—The Grand noir is one of the four varieties commonly grown in California that have colored juice, the others being Petit Bouschet, Alicante Bouschet, and Alicante Ganzin. The juice is light red, and this is supplemented by abundant pigment in the cells of the skin. It is a vigorous and productive variety. The leaves are a dull green, with more tomentum on the underside, and more deeply lobed than in the Petit Bouschet, the only other red-juiced sort with which this might be confused. The clusters are large, heavy, conical, and well filled with medium-sized round berries.

Dry table wines were produced from Grand noir in regions I, II, III, and IV. On the whole these have been unsatisfactory. They have varied from slightly to distinctly aromatic and from slightly to rather harsh, with little flavor or character. Their aromatic quality is not desirable and to most tasters is more objectionable than pleasing. All in all, these wines were very common.

The color, for which this variety has been recommended, is not exceptional, except that a portion is in solution in the juice when the fruit reaches maturity. Many varieties tested have produced wines more intense in color and more pleasing in hue. The color of Grand noir also drops out more rapidly than in most varieties.

The red sweet wines from region IV have been objectionably aromatic and only ordinary. On the basis of results to date, Grand noir should not be planted for wine making.

*Grec rouge*.—The Grec rouge at Davis, though a fair producer, is entirely unsuited to wine production. The fruit is pinkish, but can usually be made into white wines by careful crushing and early pressing. The skins are fairly tough; grapes reach the crusher in good condition; but the juice yield is only

moderate. Ripening is fairly slow, and at even moderate sugar concentration the acid content is below 0.5 per cent. The wines are accordingly thin and flat. Besides, they are practically devoid of flavor. Because of its failure to achieve a high sugar concentration, *Grec rouge* is not likely to be useful for wine making, even as sherry material. Since the variety is entirely unsuited for table wines, plantings are undesirable.

*Grosse bleue*.—At Davis this variety has ripened about midseason. Although the grapes were of fair acidity the wines, probably because of active acid reduction, were deficient in acid. They lacked distinction in other respects, too, not having much color, and taking on an oxidized flavor very easily. At Davis the vines have been small producers. No plantings are recommended.

*Kadarka*.—In California, Kadarka has not been tried under conditions that make it suitable for table wine. In Europe it is useful, especially in Hungary,<sup>63</sup> where it is used alone or, when lacking in color, is blended with Blue Portuguese. In Hungary its wines, high in extract and alcohol, are among the most reputed. A possible explanation of its success there may be the cool growing conditions that counterbalance its natural deficiency in color content and acidity. The blending with Blue Portuguese is probably also to correct for the sugar deficiency. Under growing conditions as favorable as those of region IV in California it is deficient in acid, alcohol, and flavor. Having been very low in acid in the cool season of 1935, it is unlikely to prove suitable for regions II and III. It should, however, be tested in I.

The grapes reach the crusher in good condition, are easily crushed, and have a good juice yield. The table wine has all been undesirable in color, flavor, and acidity; and the single dessert wine made has likewise been below average.

No plantings are now recommended, since other varieties are more useful. This corroborates the experience of Hilgard, who failed to find a suitable location for Kadarka in California. Bioletti's recommendation<sup>64</sup> of southern California as a suitable location was based on observation of the grapes and not on the wines.

*Koptcha*.—Koptcha, an early-ripening variety, has long clusters somewhat loosely set with small berries. The fruit reaches the crusher in good condition. The musts have a good acidity.

In region IV the Koptcha has produced mild, pleasing wines of distinct aroma and flavor. Beyond these properties they were not particularly harmonious. They have, however, shown sufficient promise to warrant further tests in somewhat cooler areas, provided the variety can be made to bear regularly.

Koptcha has unusual vigor. At Davis the vines have been very irregular in bearing. Long pruning with thinning to regulate the crop has been necessary to insure full crops season after season and to prevent overbearing in the years of favorable set.

The variety is not recommended for commercial planting until further trials have been made. It may not prove manageable enough, from the viticultural point of view, to be of much interest anywhere.

<sup>63</sup> Teleki, M. A. *Le point de vue hongrois*. Congrès international de Viticulture, Paris, 1937. p. 222-33. Librairie Universitaire, J. Gamber, Paris, France.

<sup>64</sup> See citation in footnote 17, p. 496.

*Lambrusche Langhe.*—This is one of several seedling sorts grown in various parts of Italy. The principal area is the province of Emilia. It is a vigorous grower and produces well.

The variety has been tested in region V. Since, unfortunately, the lots were somewhat immature each year, the wines are deficient in alcohol; in addition, they have contained barely enough acid for balanced table wines. This lack of balance more than offsets the distinct, pleasing flavor.

The variety does not appear to offer any promise under California conditions, since it will probably not be sufficiently well balanced anywhere to produce more than an ordinary product.

*Lenoir.*—This grape is a very vigorous grower and when pruned to canes is highly productive. Its clusters are medium-sized, well filled with small thin-skinned berries. The fruit, however, is resistant to unfavorable weather. The juice is intensely red.

The musts from region IV were decidedly deficient in acid. The wines were heavy, rough, and flat, with a distinguishable aromatic American flavor. The color was only moderately intense in the new wine and dropped rapidly.

Musts from region I were well supplied with acid. The wines were fairly well balanced, intensely colored, but rough, harsh, and very aromatic. They are entirely unsuited for marketing, since the consumers would not appreciate their peculiar flavor and aroma.

Even in blending, the aromatic properties come through. The color, too, is not sufficiently stable. In color, tannin, and body the Lenoir is far surpassed for blending by Salvador. The color of the latter wine is not only more intense, but far more stable. With Salvador, too, the per cent used in blending can be kept low enough to avoid tainting the blend with the aromatic American flavor.

The Lenoir did not succeed in any of the tests conducted by Hilgard or by the present investigators. It is not recommended as a fruiting sort. Its properties as a rootstock, especially for table grapes, are being tested.

*Macaroli.*—The Macaroli is a large-clusters, large-berried, late-maturing variety. The grapes are fleshy and the juice yield is small. The vines are vigorous and productive.

In four years out of six the Macaroli has failed to sugar its fruit sufficiently for balanced dry table wine in region IV. This was true even with very late (October 21) harvesting and with only moderately heavy crops.

The wines as produced at Davis have had but little flavor or character and have always been poorly balanced. They were thin and acid; or, when normal in alcoholic content, they have been flat—at best, very plain *vin ordinaire*.

This variety is wholly unsuited for California. In the cooler areas it will not ripen, and where it does ripen its acid content will be too low.

*Marzemino.*—The Marzemino, a midseason grape, produces only moderately well in region IV. The clusters are medium-sized; the berries closely set, medium-sized, and black, with a fairly thick skin. Little difficulty is experienced in crushing unless the grapes are left on the vines so long that they shrivel or raisin. The juice yield is average.

Under region-IV conditions the musts are very low in acid and high in pH. The wines taste rather fruity in spite of their low acid; but the balance is

unsatisfactory, and the high pH of the must does not make for a product of low volatile acidity.

The Marzemino is unsatisfactory for dry red table wine in regions IV and V, and probably in the cooler districts as well. It has not been, but probably should be, tested in III. Its composition in region IV indicates, however, that other varieties will prove better balanced for red table wine in such districts. Its low acid at only moderate Balling readings indicates poor ripening under cooler conditions.

*Mataro*.—The Mataro, a fairly late-ripening variety of good production, resists mildew somewhat better than the Carignane. Widely planted in California, it is easily recognized in the vineyard by the upright growth of its canes. The grapes do not easily sunburn or raisin, though they will do so in the San Joaquin Valley in hot years because of the lack of foliage. The clusters are large and winged; the berries medium-sized. The groups ordinarily reach the winery in good condition and crush easily, with a good juice yield.

In regions I and II the color is seldom deficient, whereas in IV and V it is usually too low. The musts from I and II have been so deficient in sugar content as to produce an unbalanced wine. The wines from I and II have a slightly distinct, sometimes even recognizable, but not always agreeable flavor. At best they can be considered only satisfactory, average, red table wines. They have no particular merit over Carignane, which also has a slightly distinct and not too desirable character; and in fact the Mataro wines from the same vineyard are usually less desirable. Bioletti recommended against planting the variety in California.

An occasional good-quality red dessert wine has been produced in regions IV and V, but in general the color is too deficient.

As far as vine growth and quality of the must are concerned, the Mataro may sometimes be substituted (chiefly in foggy districts) for the Carignane in regions I and II, but only for the production of average red table wines. It should not be planted under present circumstances.

*Meunier*.—The Meunier, an early-ripening variety, is probably related to the Pinots. It matures before other varieties, including the Pinot noir. The bunches are small and compact; the berries small, juicy, and usually clean and free from spoilage. The juice yield is good, and the grapes are easily crushed. In warm seasons they raisin badly even in early September. The variety is only moderately productive.

The samples from region IV have all been harvested in August. When picked early enough, Meunier has sufficient acidity for table wine; but the pH is high. The resulting wines lose their acidity rather rapidly, and the finished product is flat. It is moderate in color and has a fairly distinctive flavor.

The Meunier has no place in California vineyards except in the very coolest locations, and there only to extend the length of the picking season with an early-ripening variety. Under these conditions the quality would be satisfactory though not of the highest standard. The propensity to drop acidity shortly after fermentation may be associated with the high pH of the musts and the resulting mixed fermentation.

*Negro Amaro*.—The Negro Amaro retains high acidity and low pH in region IV at full maturity. As a result its table wines have been fruity, refresh-

ing, and well balanced. They have also possessed sufficient aroma, flavor, and character for at least average quality, and some have been above average.

If this variety would produce economically, it might be very promising, especially in region IV. Unfortunately the fruiting habit is against it. The clusters are very small—only nubbins—and the vine must be pruned long to produce a full crop. Pruning and harvesting would therefore be expensive as compared with varieties of comparable quality. Negro Amaro is not recommended.

*Neiretta*.—The Neiretta came from northwestern Italy, where it is used extensively for common table wines. Productivity and intense color have been its chief merits.

The clusters are large, compactly set with medium-sized, thin-skinned berries. The fruit matures late, though in years of early hot conditions it ripens in midseason. It has regularly reached the crusher in good condition.

The musts from region IV have been poorly balanced for dry table wines—too high in pH, too low in total acidity, or both. As a result they have been practically neutral, lacking in freshness and character, flat, and very common. Not one has merited a rating of standard. The extreme variation in color largely results from the irregularity of maturity at which the grapes have been harvested and from the difference in color standards when wines of low or high brightness are compared.

The variety is not recommended for California. In region IV and probably in III and V its wines are common; and in I and II it will not ripen regularly or sufficiently early.

*Pagadebito*.—The Pagadebito is a vigorous, heavy-producing sort. It leafs out somewhat later than the average, and its fruit matures after midseason. The clusters are medium-sized and well filled. The berries are small, round, and almost hard, with a very thick and astringent skin. The juice yield is barely average. The fruit resists disease and unfavorable climatic conditions and reaches the crusher in good condition.

The grapes attain only a moderate Balling degree and have a low total acidity. The pH of the musts is much too high for a red table wine, although no particular difficulty has been experienced in the fermentations.

The table wines from regions I, IV, and V have been characterized by lack of freshness and of acidity, by harshness or roughness, and by plain to ordinary quality. Their richness in both tannin and color might suggest usefulness as a blending wine. They are too harsh and flat, however, for this purpose, since a blending wine must add something without subtracting quality.

As a red dessert wine the product of the Pagadebito was ordinary at best. The flavor was poor, and the wine did not soften as it should for this type. The extremely high pH made the color an undesirable reddish blue. The variety is not recommended. Hilgard<sup>16</sup> mentions it as a newly imported variety. Bioletti does not mention it in his review of the varieties suitable for San Joaquin Valley conditions in 1898<sup>17</sup> but does recommend it for dry table wines in his 1907 report.<sup>18</sup> This latter recommendation is therefore probably based on a limited amount of experience and is unwarranted in view of the present results.

<sup>16</sup> See citation in footnote 16, p. 496.

<sup>17</sup> See citation in footnote 17, p. 496.

<sup>18</sup> See citation in footnote 18, p. 496.

*Petit Bouschet*.—The Petit Bouschet produces well, is moderately vigorous, and has usually more hardy vines than Alicante Bouschet. Like the latter it has color not only in the skin, but also in the juice. The fruit is clean, but resists handling injuries only moderately. The fruit ripens before Alicante Bouschet and if left on the vines shrivels and becomes soft. Even so it crushes readily, and the juice yield is good.

The table wines have been coarse, heavy, astringent, and lacking in character regardless of environment. Even the wines from region II were deficient in acid. The slightly aromatic property, though not so pronounced as in Alicante Bouschet, is nevertheless objectionable. The dessert wines from region IV were just as devoid of interest as the table wines, being coarse and common.

The color was intense and appears somewhat more stable than that of the Alicante Bouschet.

The Petit Bouschet is not to be recommended anywhere, even for blending for color. From a viticultural point of view alone it is certainly less desirable than either Alicante Bouschet or Grand noir.

*Petite Verdot*.—The Petite Verdot is of only average vigor. On the more fertile soils the crops have been moderate; on the shallower soils, light. At Davis the vines are very small producers. Since the growth and foliage leave them open, exposing the fruit, sunburn is sometimes severe. The clusters are medium-sized, and the berries below medium. The grapes are easily crushed.

The table wines from regions I and IV have not been particularly good. Despite a distinct flavor, they have not been well proportioned in other respects, so that the quality has been commonplace. The color is satisfactory. The wines are astringent and somewhat coarse. Perhaps too few tests have been made in intermediate regions; but no very good wine was produced. This checks with Hilgard's experience, which indicated it as being useful only for blending with wines requiring tannin.

In region I the Petite Verdot will produce a standard though slow-maturing and rough wine. In view of the low yields, this is not enough. Pending further tests, the variety should not be planted, especially not in the interior valleys and probably not in the cooler locations. Bioletti recommends a Verdot for red table wines in the coast counties; but whether this was the same as the variety tested here is not known.

*Pfeffer*.—Mr. W. Pfeffer first grew this variety in California. Its European antecedents have not been definitely established.

The Pfeffer is vigorous, but requires very long pruning for moderate crops. The clusters are medium-large, long-conical, sometimes shouldered, and rather closely set with short-oval, small berries. The fruit ripens late. It has reached the crusher in good condition.

Most of the samples came from region I. Only in the very warm year 1936 was maturity normal. On the whole the wines have not been satisfactory. Though distinct in aroma, fruity, clean, and pleasant, they have lacked fullness, balance, and finish. Even the sample of 1936 and the one from region III in 1939, containing 12 per cent or more of alcohol, were only average table wines. They, like the other lighter lots, had a hardness that never left them.

The aroma was distinctly recognizable in almost all lots. For this property, however, Pfeffer cannot compare in delicacy and excellence with Pinot noir,

Cabernet, or even Gamay. The aroma does not blend in with the other properties and yield the harmonious end product expected. In fruit just turning color the aroma has a Cabernetlike pungency. Toward maturity, this property becomes less marked. It is recognizable in the wine.

For the most part these wines possessed only sufficient color to be acceptable as pink or *rosé* wines. Only the very heaviest lots approached the coloring of normal red table wines. Since these lots were from the coolest region of our state, there can be no doubt that the variety lacks color.

On the basis of its period of maturing, its productivity, and the character and quality of its wines, Pfeffer cannot be recommended for region I. There it will be surpassed by several really quality varieties. The same will be even more true in region II.

In region III, Pfeffer is not sufficiently productive; and in IV and V it will produce only relatively small crops of poorly colored fruit.

*Picpoule noir*.—The Picpoule noir, a heavy-producing sort, has apparently never been grown in California, except in test plots. Its late ripening limits its adaptation abroad to the south of France, and in California restricts its possible adaptation to regions II, III, and IV. It is a vigorous, upright grower and fruits with short-spur pruning. It is very subject to mildew. Being fairly resistant to unfavorable weather conditions and handling injuries, it reaches the crusher in good condition.

The bunches are very large, and the berries above average in size and firm. The fruit crushes easily, however, and the juice yield is above average. No difficulty has been experienced in the fermentation. The wine, however, lacks almost everything except alcohol, acid, and body. It is mildly vinous, seriously lacks color, and has not even sufficient character for bulk pink wines. This variety should not be planted anywhere in California.

*Pinot Pernand*.—This closely resembles the Pinot noir and Meunier. It ripens about the same time, very early, and has practically the same composition of must. The Pernand differs from the Pinot noir in that its mature leaves are much rougher, show considerable contortion between the veins, and its clusters are more compact and heavier. The brilliant, dark green of its almost glabrous leaves distinguishes it from the dull, gray-green, heavily tomentose leaves of Meunier and Pinot Saint George.

The musts of region IV are of fair acidity at moderate sugar concentration when the grapes are harvested before September 1. Only a single sample from region I was tested. This had a high pH and too much sugar on September 10. The wines have all dropped their acidity very quickly; and the resultant product has been flat, unpalatable, and only ordinary. The new wines tend to become oxidized. In region IV the color has been too low for normal red wines. The product sometimes has a true Pinot aroma despite the unfavorable composition.

Hilgard's results<sup>28</sup> support the conclusion that the Pinot Pernand should be planted only in the very coolest regions. Since Pinot noir has a slightly better color, there appears to be no reason for planting Pinot Pernand.

*Pinot Saint George*.—Pinot Saint George is probably a variation from the true Pinot—the Pinot noir, to which it is vastly inferior in all respects except

<sup>28</sup> See citation in footnote 16, p. 496.

productivity. Indeed, the two varieties have nothing in common beyond the first part of their name.

The Pinot Saint George is a moderate grower and a good producer. The clusters are large-medium, long-conical, winged, and compactly set with small, round berries. The compact clusters are very susceptible to bunch rot. The fruit ripens 3 weeks to a month later than the true Pinot.

This variety can be distinguished from Pinot noir by the coloring of the shoots and leaves, the shape and size of the clusters and cluster parts. In the Saint George the shoots and leaves appear whitish green because of the hairy coating of the young leaves and the long hairs on the young shoots, tendrils, and leafstalks. The mature leaves have a mat of hair underneath. The young leaves of the Pinot noir have a fair coating of hair below and a few hairs above; but the young shoots, tendrils, and leafstalks are shiny, with only an occasional hair. The mature leaves are a glossy light green beneath, with but few hairs. The clusters of the Saint George are regularly winged; usually the wing is divided, while only a part of the Pinot noir clusters are winged. The peduncle or stem of the Saint George clusters is usually less than  $\frac{3}{4}$  inch in length.

The musts of the Pinot Saint George were generally poorly suited for dry table wines. Irrespective of source, the fruit at normal maturity had a low acid content and a relatively high pH.

Even the wines from regions I and II possessed a common flavor and were rough, without character, and flat. They were ordinary table wines.

The wines from region III had about the same quality as those of I and II—no properties that would tend to elevate them. The normal red table wines of region IV were generally somewhat heavier, rough, flat, and lacking in finish. They, too, were commonplace.

During 1940 and 1941 eight lots from region IV were harvested earlier and pressed immediately to produce pink wines. This treatment did not materially improve the aroma, flavor, or finish of the mature wines.

Because of general poor quality of its product the Pinot Saint George cannot be recommended for planting. Growers who wish to produce red Pinot wines should be sure to obtain planting material of the Pinot noir.

*Tinta amarela*.—The Tinta amarella is another variety from the Alto Douro Valley of Portugal. Its clusters are very compact, heavy, conical, and large to medium. The berries are medium-sized, black, round to slightly oval, firm but not tough. Ripening in late midseason at Davis, the fruit is often caught by unfavorable weather conditions and rains. At such times, decay in the very tight clusters is rapid and severe. Primarily for this reason the variety is not recommended.

In regions IV and V the Tinta amarella is unsuited for dry table wines. Its musts lack both acid and flavor for these types. Its fruit is too susceptible to decay for wine production in the coastal counties.

Well-matured grapes of regions IV and V are, however, almost ideally balanced for red dessert wines. The sugar is high, the acid moderate, the tannin low, and the flavor very pleasing. These dessert wines were full-bodied, well rounded, mellow, and nicely colored. They resemble those of the Tinta Madeira, but have not possessed an equally interesting balance. For viticultural reasons alone, the latter variety is preferred.

## VARIETIES REQUIRING FURTHER TESTING

Several varieties cannot be recommended or disqualified because only a restricted number of samples have been collected or only a few regions have been tested in the present studies. Some of the varieties listed here are probably of no value; but a few may, on further trial, prove useful. No plantings are recommended at present except on an experimental scale. A few of these varieties were recommended at one time or another by some previous investigator. The present studies have not been sufficiently conclusive to prove or disprove these earlier recommendations.

### WHITE VARIETIES NOT FULLY TESTED

Incompletely tested white varieties include Boal Madeira, Catarratto, Erba-lice Caluso, Ezerjo, Furmint, Grillo, Honigler, Muscat Terracina, Orleans, and Walschriesling. Analyses of musts and wines of these varieties are given in table 22.

*Boal Madeira*.—The Boal Madeira, a vigorous grower, has produced large crops regularly at Davis. It requires short-spur pruning. The clusters are large, heavy, short-conical, and well filled with medium-sized, short-oval, yellow-green berries. The fruit ripens in late midseason. With careful handling it reaches the crusher in good condition; but it will not withstand wet weather and is subject to mildew. In case of early rains the fruit rots very badly.

In the more favorable years 1935 and 1937, the dry table wines were slightly distinct in aroma and fruity in flavor. They were average, common wines with little character and none too fresh a flavor. In the other years—1936, 1938, and 1939—the wines were bland, flat, and markedly subject to oxidation.

When baked, the sherries proved light, rather well balanced, and palatable. They, too, have suffered from plainness. Hilgard found the Verdelho generally superior to the Boal Madeira, but Bioletti recommended the Boal and omitted Verdelho as a dessert-wine grape—probably because of the small production of the latter.

The dry table wines of the Boal Madeira have not shown sufficient character and quality to warrant plantings. The sherries have not equalled those of Palomino or Inzolia. These other varieties are equally or more productive; hence there also appears to be little place for the Boal in California for producing this type of wine. The conditions in regions IV and V should be investigated more carefully for a possible favorable habitat for this variety.

*Catarratto*.—The Catarratto is grown extensively in western Sicily. Although probably introduced before 1890, it has no record in California. The fact that Bioletti (1907) recommended other varieties introduced at the same time, but failed to mention the Catarratto, may be significant. Its country of origin would indicate an adaptation to warm locations.

The vines are vigorous and productive; the clusters large, long-conical, shouldered, and compact. Often the tendril on the peduncle is fruitful enough to form a wing of the cluster. The berries are small to medium, round, and greenish yellow, with a rather thick, tough skin. The fairly firm pulp, the tough skin, and the firm attachment render this fruit resistant to unfavorable

(Text continued on page 656)

TABLE 22  
COMPOSITION OF MUSTS AND WINES OF WHITE VARIETIES WHICH HAVE NOT BEEN FULLY TESTED

Region	Number of samples	Average harvest dates and year	Must			Wine			
			Balling degrees	Total acid, grains per 100 cc	pH	Alcohol, per cent	Fixed acid, grains per 100 cc	Tannin, grains per 100 cc	Color intensity*
Boal Madeira									
IV	1	Sept. 17, 1936	22.4	0.70	10.1	0.58	2.3	0.03	Slightly distinct aroma; above average quality
IV	2	Sept. 22, 1936	24.5	37	3.91	14.4	30	2.7	0.03
IV	2	Oct. 9, 1937	21.9	59	3.59	13.0	38	2.0	0.03
IV	3	Oct. 5, 1938	21.3	59	3.90	12.1	55	2.5	0.05
IV	4	Sept. 13, 1939	23.8	59	3.52	..	43	2.3	0.03
IV	1	Oct. 29, 1941	25.7	6.65	3.66	19.7†	0.46	6.9	0.05
Cataratto									
IV	1	Sept. 23, 1935	20.0	0.53	8.6	0.40	1.9	0.05	Fair flavor; thin; pleasant, but lacks character
IV	1	Sept. 13, 1936	21.0	0.50	3.20	9.3	49		Fairly fresh, thin, only ordinary quality
IV	1	Sept. 26, 1937	21.8	0.60	3.52	11.3	51	1.9	0.04
V	1	Aug. 27, 1937	21.3	0.74	3.86	11.5	51	2.2	0.03
IV	1	Oct. 3, 1938	20.1	0.64	3.34	12.7	53	2.3	0.07
V	1	Aug. 14, 1938	19.9	0.57	3.39	10.8	56	2.3	0.06
IV	1	Oct. 26, 1939	25.4	0.57	3.55	14.4	46	2.8	0.03
V	1	Aug. 17, 1939	20.8	0.69	3.53	11.2	57	2.2	0.05
IV	1	Sept. 5, 1940	19.4	1.22	3.36	10.2	89	2.8	0.03
IV	1	Oct. 30, 1941	28.2	0.61	3.51	13.4	0.39	2.8	0.05

\* For footnotes to table see page 355.

Erbaulace Caluso										Ercero										Furmint											
IV	1	Sept. 17, 1935	18.4	0.91	-	8.7	0.43	2.2	0.03	Distinct, not balanced																					
IV	1	Oct. 1, 1936	26.2	50	3.86	18.4†	41	13.3	.02	Well-balanced white dessert wine, average flavor																					
IV	1	Oct. 15, 1937	21.2	55	3.31	12.3	40	2.5	.03	Ordinary flavor and quality																					
IV	1	Oct. 10, 1938	22.2	65	3.32	12.8	55	2.4	.05	Balanced, average character and quality																					
IV	1	Aug. 21, 1939	22.7	71	3.20	12.3	64	2.4	.03	Rather tart; not very distinctive, palatable																					
IV	2	Sept. 14, 1940	22.5	75	3.46	21.0†	33	12.9	.03	Fruity; distinct flavor, good quality. Duplicate as table wine lacks flavor																					
IV	1	Oct. 30, 1941	24.9	0.67	3.28	18.1†	0.47	9.9	.04	Ordinary white sweet wine, lacks distinct flavor																					
Ercero										Light, but slightly distinct; pleasant																					
IV	1	Oct. 8, 1938	19.7	0.49	3.37	12.1	0.34	2.2	0.06	36																					
IV	1	Aug. 16, 1939	19.7	79	3.25	10.8	46	2.0	.03	Light, mild aroma, flavor, earthy																					
IV	1	Oct. 8, 1940	23.3	52	3.58	13.1	55	2.5	.02	Distinct aroma, good flavor; overripe taste																					
IV	1	Sept. 19, 1941	24.3	0.65	3.30	13.7	0.51	2.7	0.08	12	Fruity, mild aroma and flavor, balanced																				
Furmint										Fair flavor, delicate, smooth; pleasing																					
IV	1	Oct. 7, 1938	25.0	0.61	3.67	13.0	0.43	2.7	0.03	22																					
IV	1	Oct. 3, 1939	24.0	60	3.68	12.9	48	3.0	.07	Average flavor; rich; full body; soft																					
IV	1	Sept. 16, 1940	24.7	54	3.85	12.0	52	6.5	.01	Rich, slightly distinct flavor; soft; pleasing																					
IV	1	Oct. 20, 1941	28.3	0.87	3.85	13.7	0.50	7.6	0.05	38	Distinct aroma, rich, promising natural sweet wine																				
Grollo										Average quality sherry material, some aroma; flat																					
IV	1	Sept. 14, 1938	24.2	0.52	3.47	13.7	0.37	3.0	0.06	28																					
IV	2	Sept. 27, 1939	27.4	59	3.26	18.1†	45	2.3	.03	Good sherry material; distinct and fruity flavor																					
IV	1	Sept. 5, 1940	22.5	75	3.36	12.5	56	2.4	.01	Balanced, lacks character; oxidizes easily																					
IV	1	Oct. 28, 1940	28.9	65	3.58	18.0†	35	16.4	.02	Fruity white sweet; good quality sweet sherry																					
IV	1	Oct. 30, 1941	28.5	0.58	3.51	16.8†	0.48	2.7	0.05	10	Distinct varietal flavor; very good sherry																				

(Continued on following page)

TABLE 22.—(Continued)

Region	Number of samples	Average harvest date and year	Must			Wine				
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol, per cent	Fixed acid, grains per 100 cc	Extract, grains per 100 cc	Tannin,igrams per 100 cc	Color intensity*
Honigler										
IV	1	Oct. 17, 1938	22.2	0.43	3.50	12.5	0.50	2.6	0.05	15
IV	1	Aug. 21, 1939	21.6	0.55	3.45	10.8	.51	2.2	.03	13
IV	1	Aug. 19, 1940	21.0	0.63	3.45	11.6	.55	2.2	.02	9
IV	1	Sept. 26, 1941	22.5	0.60	3.49	12.6	0.57	2.1	0.05	7
Muscat Terracina										
IV	1	Sept. 23, 1937	22.2	0.55	3.80	21.3†	0.26	10.6	0.05	15
IV	1	Oct. 10, 1938	17.4	0.40	3.64	9.7	.31	2.2	.05	18
IV	1	Sept. 25, 1939	22.5	0.49	3.56	20.2†	.33	9.0	.02	52
IV	1	Oct. 28, 1940	21.4	0.44	3.73	20.6†	.30	6.4	.03	14
IV	1	Oct. 29, 1941	20.5	0.51	3.52	11.2	.44	2.1	.04	10
V	1	Aug. 21, 1941	20.7	0.49	3.57	19.0†	0.34	13.8	0.05	52
Orleans										
IV	1	Oct. 3, 1938	23.1	0.45	3.76	13.5	0.43	2.4	0.04	12
IV	1	Aug. 31, 1939	22.9	0.72	3.21	11.8	.44	1.9	.02	71
IV	1	Aug. 28, 1940	23.1	0.73	3.22	11.7	.68	2.6	.02	9
IV	1	Sept. 30, 1941	23.5	0.59	3.42	13.6	0.51	2.4	0.06	6

## Walschriesling

IV	2	Sept. 20, 1935	21.8	0.47	...	10.7	0.35	1.7	0.04	Distinct aroma; pleasant flavor, soft, but flat	
IV	1	Aug. 23, 1936	22.3	60	3.62	11.9	35	2.1	0.3	Fair flavor; distinct, not balanced; average quality	
IV	1	Sept. 20, 1937	23.3	46	3.65	12.4	33	2.1	0.3	Fruity, distinct, varietal flavor; light; very pleasant	
IV	1	Aug. 16, 1939	21.4	.68	3.18	11.5	.59	1.9	.04	Fruity, gray flavor; a good table wine	
IV	1	Aug. 14, 1940	21.9	.61	3.28	12.0	.48	2.2	.01	Distinct, fruity flavor; clean, light; good quality	
IV	1	Sept. 8, 1941	24.3	0.61	3.38	14.4	0.54	2.4	0.03	Very distinct, pleasant flavor, but heavy	

Determined in a color comparator using an arbutaluric color standard made from Eastman ABC dyes; the color intensity increases as the figures increase.

Fermentation arrested by the addition of grape brandy.

weather and to handling injuries. The variety matures late; but except for failure to mature in cool locations this disadvantage is not serious.

The wines from regions IV and V have been uniformly neutral in flavor, mild in character, but fair in acidity. The grapes, although late maturing, have been sound, the musts have fermented well, and the wines have aged rapidly and without difficulty. Catarratto should be tested further for brandy and sherry. With careful timing of the harvest it may produce a must fairly well balanced for commercial brandy. The neutral character of the product indicates that the greatest value may be for blending. In warm seasons in region V Catarratto may also prove useful for dessert wines.

Its neutral character and its late maturing make it undesirable for table wines.

*Erbaluce Caluso*.—The Erbaluce Caluso is a white variety, used in northern Italy to produce the natural sweet and distinctive wine of Caluso. The vines, though vigorous, are only fairly productive unless cane-pruned. The clusters are medium-sized, pyramidal, and well filled with medium-sized, round, thick-skinned berries, which may take on a rose color or blush when mature.

At Davis the wines have been variable—in some seasons distinctive in flavor and good in quality, in other years just ordinary and not too well balanced for either table or dessert wines. The variation in crop is partially responsible for this condition.

In region IV the musts have usually good acidity when normally mature. This, together with the distinctive flavor obtained in the 1935 and 1940 wines, may justify further testing. Possibly the variety will be best in region V for dessert wine. At present, however, it cannot be recommended for California. This view is partially confirmed by the fact that this grape had been introduced by Hilgard and was therefore presumably known to Bioletti, who in 1907 does not list it among his nineteen recommended white wine-grape varieties. Earlier, however, Bioletti<sup>10</sup> mentions it as producing good crops in region IV in southern California.

*Ezerjo*.—Ezerjo is vigorous but only moderately productive. According to Teleki<sup>11</sup> it is a native of Hungary, where it produces quality white wine. The clusters are large, branching, and compact. The medium-sized, short-oval berries have a thin, tender skin that does not resist handling injuries. Unfavorable weather at maturity will cause rot. The variety is subject to raisining.

The wines from region IV, despite a pleasing aroma and flavor and some character, have not been too well balanced generally, their acid content being especially low. They have lacked fruitiness and life. The variety is therefore not adapted to such climatic conditions as those in region IV.

Nevertheless, this variety shows sufficient promise as regards character to warrant further testing in somewhat cooler areas. Its compact clusters, tender skin, and period of maturing will no doubt exclude it from region I and the cooler parts of II, but further tests in II and III are indicated. It is not suited to IV and V.

<sup>10</sup> See citation in footnote 17, p. 496.

<sup>11</sup> Teleki, Sigmund. Weinbau und Weinwirtschaft in Ungarn. 127 p. (See especially p. 83.) Oesterreichischer Wirtschaftsverlag. Kommanditgesellschaft Payer & Co., Vienna. 1937.

*Furmint*.—The soil and climate in a limited zone on the Hegyalia plateau of Hungary, the nature of the Furmint grape, and the particular method of wine making utilized make such a combination that a wine of distinction results. This is the Tokai of Europe (Tokaj or Tokay). Since the Furmint has a very thin skin, the fully mature berries dry rapidly, yielding a juice of high concentration. Tokay, the natural sweet wine of low alcohol content, is world renowned for lusciousness and perfume.

This variety is a strong grower and a moderate producer. Unfortunately its thin skin and soft texture, which have added much to its quality in Hungary, do not function to advantage here. The fruit is subject to attack by insects, which feed on its rich sweet juice, and to rot and decay. Rapid loss of water by the mature fruit also leads to raisining and objectionable flavors under most California conditions.

The musts from region IV have been high in sugar, with barely sufficient acid for a well-balanced natural sweet wine. The wines have been full-bodied and soft, delicate in flavor and mildly distinctive in aroma. The natural sweet wines, though of good quality, have lacked the pronounced perfume of the real Tokai.

The great difficulty, however, is susceptibility to rot at maturity. The cost of preventing rotten grapes from getting into the crusher would be very high, and much fruit would be lost. At Davis the grapes have had to be covered with cheesecloth and then hand-sorted before crushing. Even so, it is difficult to deliver only good grapes of high sugar content to the crusher.

On the basis of our present knowledge, Furmint cannot be recommended for California. Its outstanding quality where it succeeds may well justify further tests in cool regions by growers who are interested in it as an experiment.

*Grillo*.—The Grillo has found recognition in Sicily as a constituent of most Marsalas. It represents, however, the smaller part of the blend. There it is supposed to lend softness to the product. The vine is vigorous and produces good crops. The fruits are rather hard-textured and mature in good condition. The juice yield is below average.

Both table and dessert wines of average quality have been produced at Davis. The table wines were low in acidity and lacking in aroma and character. The sherries were slightly distinct, fruity, and well balanced. The fruitiness is the most valuable quality. The variety should be tested further for sherry production, especially in region V. It has not shown sufficient promise over several standard varieties, especially Palomino, to justify plantings at the present time.

*Honigler*.—Like the other white Hungarian varieties tested, the Honigler has a thin, tender skin. In unfavorable weather the crop will rot. Its fruit, however, has not been so much attacked by insects as the Furmint.

The musts of the fruit grown at Davis have contained barely enough acid for dry table wines and too little sugar for dessert wines. Their pH has been high. The product, however, has been moderately distinctive in aroma and flavor, clean, pleasant, harmonious, and well above average in general quality.

Because of its high productivity and the good qualities of its wines, the Honigler should be tested in regions II and III. It cannot be recommended for regions IV and V.

*Muscat Terracina*.—The Muscat Terracina is a medium grower and a heavy yielder even with spur pruning. At Davis an irregularity in bearing has made it difficult to prune for full crops each year without inducing occasional overbearing.

The clusters are medium-large, long-conical, shouldered, and completely set with medium-sized, short-oval, thick-skinned berries. When the crops have been such that the fruit has matured normally, it has reached the crusher in good condition.

The dry wines were entirely unsuccessful because of the typical muscat harshness that they showed in marked degree and because of their poor composition.

Muscateis from regions IV and V have not been wholly satisfactory. They have possessed a distinct yet only mild muscat aroma, with a rather limited character, and have been thin and not too well balanced. Some of the shortcomings can be charged to the low sugar content or immaturity of the fruit at harvesting. If this condition has resulted from overbearing, as seems to be the case, the variety should not be condemned without further testing.

The aroma and the flavor, even under the conditions of these tests, have surpassed those of Muscat of Alexandria. In these properties, however, Terracina was surpassed by Muscat Canelli and Orange Muscat. Again the matter of crop must be considered. The Terracina has consistently outyielded the Alexandria at Davis, and its yields have been more than double those of the Canelli and one half more than those of the Orange.

Further tests, evidently, should be made, with greater emphasis on yield. Without such tests no decision can be reached. Meanwhile, the variety is not recommended for planting.

*Orleans*.—The Orleans is grown in certain parts of Germany, primarily as a table grape. In earlier times it was used for wine, but now it has been all but displaced by the White Riesling or by the Sylvaner. With spur pruning it bears somewhat better than the former and about the same as the Sylvaner. The clusters are medium-sized, long-conical, fairly compactly set with firm, medium-sized, short-oval berries. The fruit has reached the crusher in good condition. The musts were, in general, of good acidity for the region. The juice yield was only fair. Because of its firmness the fruit withstands handling injuries.

Wine was produced from region IV in four seasons. In three of the years the product had a pleasant aroma and flavor and some character, but was deficient in acid. In the other season the wine was rich, with a delicate Rieslinglike aroma and flavor, good balance, and good finish.

Judging from these results this variety is not well adapted to the warm conditions of region IV. Further tests may show, however, that the Orleans will produce above-average quality table wines in regions II and III. Pending such tests, the variety is not recommended.

*Walschriesling*.—The Walschriesling is a weak grower, but very productive. The small vine, however, limits the yield. Under our conditions of wide spacing, this fact alone all but eliminates the variety from consideration.

The present tests were made only in region IV. Here the product usually had a distinct though mild varietal aroma and flavor and was soft and pleasant

in the cool seasons. In the warm seasons the wines were flat, somewhat heavy, and less pleasing. At best, these were only good table wines.

Although it has produced some very acceptable table wines in region IV, Walschriesling cannot be recommended because of its low yields. In the cooler regions the quality would no doubt be higher; but production would drop. In no case will the aroma and flavor approach the richness of a good White Riesling. The variety should not be planted anywhere without special prior testing for quality and yield.

#### **RED VARIETIES NOT FULLY TESTED**

Red varieties insufficiently tested include Affenthaler, Aglianico, Corbeau, Fogaruna, Malbec, Merlot, and Robin noir. Analyses of musts and wines of these varieties are given in table 23.

*Affenthaler*.—In the earlier work with Affenthaler, Hilgard<sup>71</sup> was impressed with its capacity of producing quality red wines in California. He made eighteen lots of it: two from Fresno, two from the Amador station, and the remainder from the coast counties. Except for the warmer locations in the coast counties and the interior, these wines were found to contain ample acid and color, were well balanced, and appeared somewhat distinctive. Near the coast they were somewhat rough, when young, but with sufficient aging developed into quality wines that kept well.

In the coastal areas the variety proved average in vigor and production, but in the interior it did not bear so well. At Davis it is a moderate producer. Despite these early favorable results, Bioletti<sup>72</sup> in 1907 failed to recommend it for California.

The clusters are medium-sized, conical, winged, and well filled with small, round, thin-skinned berries. With moderately careful handling, the fruit reaches the crusher in good condition.

As regards must composition, the present results agree well with previous work on grapes of the interior. The wines, however, have lacked the definite character and high quality ascribed to the earlier ones. Despite a slightly distinct aroma and a fruity flavor, they were deficient in acidity and color, only average in quality. In no case have they been distinctive. The color has been approximately that of a normal pink wine.

These results definitely indicate that the Affenthaler is not adapted to region IV or warmer areas. Under such conditions the quality is not high enough to offset the moderate-to-low yields. The variety may, on the basis of earlier work, deserve a place in region II and the cooler parts of III. Without further testing it is not recommended. In region I it will probably ripen too late.

*Aglianico*.—The Aglianico is an old variety. According to history, it was taken from Greece to Naples about the sixth century B. C. and it has been grown on the slopes of Mount Vesuvius ever since. To enjoy such a long period of culture it must possess something more than a tradition.

The variety ripens late. At Davis it has produced well. The clusters are large and closely set with small berries. The variety is fairly resistant to dis-

<sup>71</sup> See citation in footnote 16, p. 496.

<sup>72</sup> See citation in footnote 18, p. 496.

TABLE 23  
COMPOSITION OF MUSTS AND WINES OF RED VARIETIES WHICH HAVE NOT BEEN FULLY TESTED

Region	Number of samples	Average harvest date and year	Must			Wine			Tasting record
			Total acid, grams per 100 cc	pH	Alcohol, per cent	Fixed Extract, Tannin, acid, grams per 100 cc	Color intensity*		
Affenhalter									
IV	2	Oct. 1, 1936	22.9	0.77	. .	10.5	0.37	2.4	0.16
IV	2	Sept. 15, 1936	24.1	.53	3.40	11.0	.48	3.1	20
IV	1	Sept. 17, 1938	23.4	.83	8.44	12.0	.69	3.6	16
IV	1	Sept. 12, 1939	24.3	.69	3.15	11.8	.59	2.5	16
IV	2	Aug. 31, 1940	23.5	.78	3.29	12.0	.57	2.0	17
IV	3	Sept. 11, 1941	22.6	0.86	3.15	11.5	0.57	2.7	0.22
Aghianico									
IV	1	Oct. 18, 1938	21.6	0.72	3.37	11.0	0.42	2.6	0.14
IV	1	Sept. 20, 1939	20.0	1.21	3.02	9.9	.56	3.0	12
IV	1	Sept. 30, 1940	22.2	1.12	3.32	11.3	.58	3.1	16
IV	1	Oct. 29, 1941	22.6	1.03	3.19	11.8	0.78	3.7	0.20
Corbeau									
IV	2	Oct. 7, 1938	20.2	0.42	3.67	11.0	0.47	2.9	0.16
IV	1	Sept. 25, 1939	24.1	.49	3.67	12.2	.45	3.2	15
IV	1	Oct. 1, 1940	23.5	.54	3.79	12.4	.53	3.2	16
IV	1	Sept. 30, 1941	20.3	0.64	3.66	10.3	0.45	2.7	0.14

\* For footnotes see page 662.

Fogaruna											
IV	1	Oct.	17, 1938	20.4	0.85	3.14	10.8	0.50	2.8	0.20	5VR-9
IV	1	Sept.	12, 1939	22.1	.84	3.08	11.3	.81	2.8	27	
IV	1	Sept.	16, 1940	22.8	.80	3.44	10.9	.56	2.9	20	
IV	1	Oct.	1, 1941	22.6	0.90	3.11	11.2	0.62	3.1	0.18	
											45
											Slightly fruity, mild flavor; full-bodied; balanced

Malbec											
IV	3	Sept.	24, 1935	23.9	0.67	..	11.1	0.41	2.5	0.15	VR-22
IV	2	Sept.	19, 1936	25.1	.75	..	13.6	.60	3.8	17	3R-27
II	1	Oct.	10, 1937	21.2	.71	3.13	12.2	.70	2.5	17	R-35
IV	3	Sept.	3, 1937	23.0	.79	3.74	12.3	.35	2.6	15	3YR-14
II	1	Oct.	9, 1938	20.0	.71	2.96	10.7	.80	2.6	.17	VR-22
IV	3	Oct.	3, 1938	21.1	.51	3.69	10.7	.49	2.9	12	3VR-16
IV	3	Sept.	2, 1939	26.5	.72	3.46	11.5	.55	2.8	11	
IV	4	Sept.	10, 1940	23.6	.76	3.71	11.7	.47	3.1	.09	
IV	1	Sept.	17, 1941	21.9	0.81	3.62	11.1	0.33	3.4	0.13	
											454
											Flat; distinct Cabernetlike flavor; ordinary

Merlot											
IV	1	Sept.	23, 1935	22.8	0.34	..	11.2	0.37	2.0	0.11	5VR-19
IV	1	Sept.	20, 1937	23.4	.42	3.76	12.1	.30	2.3	13	R-10
I	1	Sept	25, 1938	21.4	.47	3.10	11.5	.24	19	R-25	
IV	1	Sept.	15, 1941	22.2	0.60	3.32	10.9	0.46	2.7	0.13	
											453
											Distinct aroma; flat; above average quality

(Concluded on following page)

TABLE 23—(Continued)

Region	Number of samples	Average harvest date, and year	Must			Wine				
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol, per cent	Fixed acid, grams per 100 cc	Extract, Tannin, grams per 100 cc	Tannin, grams per 100 cc	Color intensity*
Robin noir										
IV	1	Sept. 23, 1935	22.6	0.71	-	11.1	0.40	2.4	0.13	2Ry-S
IV	2	Sept. 7, 1936	24.7	.47	3.87	12.5	41	2.1	14	3Ry-7
IV	1	Sept. 13, 1937	25.7	.86	3.57	13.1	35	2.5	13	2R-8
IV	1	Sept. 18, 1938	21.8	.73	-	10.5	46	2.8	14	1R-6
IV	1	Aug. 16, 1939	21.3	.97	3.10	10.4	71	2.7	11	3R-4
IV	1	Aug. 19, 1940	22.7	.91	3.26	12.3	57	2.6	.031	15
IV	1	Sept. 8, 1941	24.3	1.07	3.19	12.1	0.70	3.0	0.08†	99

\* Data in left column, by the Dujardin-Sallevon wine-colorimeter following Hilgard's procedure; the observed figures have been divided into 4,000 so that the recorded figures will be proportional to intensity. Data in right column, by use of color standards and a color comparator.

† Pressed 24 hours after crushing.

eases and handling injuries and reaches the crusher in good condition. The juice yield is good. The musts are of excellent acidity and, for region IV, of moderately low pH.

The dry table wines from region IV have not been impressive. Though fair to good in balance, they have lacked the flavor, aroma, and character necessary for distinction. Only in the last year did the product contain a normal amount of color. For some reason the young wines seem to be subject to acid-reducing bacteria and lose a large percentage of their acidity.

Thus far the Aglianico has not proved adapted to region IV, even though the temperature is somewhat lower than in the area where it is grown in Italy. Further tests should be carried out both at Davis and under warmer conditions. With a somewhat better-balanced must—that is, of less acidity—the resulting wines may show greater promise. In view, however, of the more stringent color restrictions for wines in this country, its color deficiency is unlikely to recommend it to the wineries even if a better-balanced wine should be produced in another location.

At present Aglianico is not recommended for California.

*Corbeau*.—Corbeau is vigorous and, at Davis, very productive. Its medium-large clusters handle so well that the fruit usually reaches the crusher in good condition. The fruit is of medium size and closely set. It crushes easily and the juice yield is good.

In region IV the must has been rather low in acid, so that the dry table wines have not been balanced or fresh. Despite this defect their distinct aroma and flavor have been pleasant and desirable. In view of these latter properties, the variety should be tested in cooler areas. Judging, however, from its late ripening in Davis, its fruit may not mature properly in regions where the grapes retain sufficient acidity to be well balanced. Regions II and III offer the best possibilities. Late ripening also prevents use of Corbeau for red dessert wines. The color is sufficient and of a good tint despite the high pH.

*Fogaruna*.—The Fogaruna is moderately vigorous and productive. Its clusters are medium-sized, conical, and compactly set with medium-small, very firm berries. The firm texture and the thick, relatively tough skin make the berries resistant to handling injuries and unfavorable weather. The fruit each year has reached the crusher in excellent condition. It does not color till fairly late, but has ripened in sufficient time at Davis.

The musts from region IV have possessed a relatively high acid content and a low pH. The wines have been tart and fruity, with a pleasing flavor and some character. They have not been quality wines, but are interesting for their general balance and their mild but distinctive character. The variety should be tested further under conditions similar to those at Davis to determine its best adaptations.

In a slightly cooler region where it would still mature, the color should be more intense, the aroma and flavor more pronounced, and the product better balanced. Under such conditions the wine should have value not only for itself, but also for blending. At present Fogaruna is not recommended for regions I, II, and V. Further tests should be made in III and IV.

*Malbec*.—The Malbec is an early-ripening variety commonly used in the Bordeaux region of France to blend with the Cabernet Sauvignon variety. As

Peynaud<sup>38</sup> has shown, the blending of Bordeaux grapes may be intended not only to soften the predominant flavor of the Cabernet but also to balance the acidity of the must and more particularly to get the proper ratio of tartaric and malic acids.

The variety produced well at Davis, but Hilgard found it a very poor producer in other localities. Although the skins are rather thin, the grapes do not spoil easily. The clusters are medium-sized and the berries loosely set. The juice yield is good.

The wines have a surprisingly distinct flavor, strongly suggestive of Cabernet, though neither so strong nor so well balanced. Although of good flavor, the product does not regularly have a high enough acid for making red table wine in region IV. It should probably be tried for a red dessert wine under these climatic conditions. On the other hand, the musts from region II are of good acidity and produce standard though not high-quality wine.

The studies thus far justify a further examination into the possibility of growing this variety in cool locations such as regions I and II, and of utilizing it for red dessert wine in IV and V. At present plantings are not recommended, since other varieties have equal or greater potentialities. Hilgard's failure to secure production, because of coulure, should also be considered.

*Merlot*.—The Merlot has been insufficiently tested in California. It is a Bordeaux variety, which in France produces an average wine.

Here it is a small producer and, under region-IV conditions, very deficient in acid. Hilgard's reports are similar in this respect. The flavor, however, is distinct, reminding one faintly of Cabernet.

Merlot should be tested further in regions I and II, where its mild-flavored but slightly distinctive wines may find a place. Indications are, however, that it will not make a high-quality wine even in a district where its musts will be well balanced.

*Robin noir*.—The Robin noir is moderately productive and matures early. The clusters are long and medium-large, and they handle well if picked early. The fruit, if left on the vines till midseason, is subject to raisining. The juice yield is good.

In region IV the balance of sugar and acid in the mature fruit adapts it for table-wine production except in a very warm season such as 1936, when it is too low in acid. The color intensity has been low, sufficient only for well-colored pink wines. The tannin content, after several days of fermentation on the skins, has also been equal in magnitude to that of normal pink wines. The product tends, as with Pinot noir, to lose considerable acidity. Acid-reducing bacteria are apparently involved. Earlier racking from the lees and addition of a little sulfur dioxide after fermentation may prevent this difficulty.

The wines were distinctive and pleasing in flavor, well balanced, fresh, and smooth—good pink wines.

On the basis of results to date the Robin noir should be tested further in regions I, II, and the coolest parts of III. There it may develop sufficient color and tannin for a delicate, well-balanced, red table wine. Such tests may show, however, that it has other faults, not now apparent.

<sup>38</sup> Peynaud, E. L'acide malique dans les moûts et les vins de Bordeaux. Société des Sciences Physiques et Naturelles de Bordeaux, Procès-Verbaux 1937-38:75-79, 89-94.

In regions III and IV it is adapted for pink wines only. Moreover, the pink wines of several high-yielding, standard black varieties are almost or fully equal to these in quality. Its planting in these regions is therefore not recommended.

This variety should not be planted in region V, where it will lack both color and acid.

#### USE OF TABLE GRAPES FOR WINE

The deficiency of wine grapes during the post-Prohibition period has led to the widespread use of table grapes for wine making. So long as these varieties are used solely for distilling material to produce nonbeverage grape brandy for use in the arresting of the fermentation of dessert wines, their wine-making quality is of minor importance. Not all the musts of the table-grape varieties, however, are fermented solely for the above purpose; some are used for making dessert wines, beverage brandy, or even table wines. The utility of the table-grape varieties will therefore be briefly considered. Since all, or nearly all, the table grapes of California are grown in regions IV and V, the problem of their composition is restricted to these areas. Limited amounts of Chasselas doré are found in II and III.

The chief characteristics of table-grape varieties are their mild flavor, their eating quality, and their low acidity at rather low sugar concentrations. The Balling-acid ratio of this type of grape is therefore high. Their ultimate sugar concentration is likewise low. Even an early-ripening table-grape variety such as Luglienga rarely attains a Balling reading of more than 23° or 24°. Since table-grape varieties also usually have a high pH, they are more susceptible to spoilage during and after fermentation than musts of lower original pH.

Another disadvantage of table grapes has been the fact that all the packing-shed culls have been diverted to winery use—frequently when bruised and several days old. Likewise the clusters not up to shipping quality are left on the vines and later diverted to the winery. Still another handicap of table grapes is that notable quantities have been shipped in gondola trucks over long distances. Under these circumstances they bruise badly despite their naturally firm texture.

The flavor of wines produced from table grapes is uniformly poor. Because of their low acidity they frequently develop bacterial contamination during fermentation or storage. The low acidity of their musts results in flat-tasting wines. Finally, their natural mildness of flavor can produce only mild-flavored wines. That the lack of acidity is not the only shortcoming can be proved by ameliorating the must with acidity before fermentation: the wines, though better balanced, are still neutral and ordinary. From the standpoint of the winery it would be better if no table grapes, except perhaps Thompson Seedless, were ever crushed. For economic reasons, however, many will probably be used. As far as possible, they should be utilized for distilling material. The next most practical use is for sherry material.

#### WHITE TABLE-GRAPE VARIETIES

White varieties include Almeria (Ohanez), Chasselas doré, Malaga, and Thompson Seedless. The Servant, which may also be considered as a table grape, has been previously discussed. Representative analyses of musts and

TABLE 24  
COMPOSITION OF MUSTS AND WINES FROM WHITE TABLE GRAPES

Region	Number of samples	Average harvest date and year	Must			Wine			
			Balling degrees	Total solids, grams per 100 cc	pH	Alcohol per cent	Fixed acid, grams per 100 cc	Extract, grams per 100 cc	Tannin, grams per 100 cc
Chasselas doré									
I	1	Oct. 16, 1935	20.7	0.38	-	9.5	0.32	1.9	0.02
II	3	Sept. 29, 1935	23.9	0.35	-	12.1	0.37	2.1	0.03
III	1	Oct. 2, 1935	22.6	0.26	-	11.0	0.32	2.1	0.06
II	2	Sept. 19, 1936	24.7	0.31	4.01	13.6	0.34	2.4	0.03
IV	8	Sept. 22, 1936	23.3	0.45	3.97	10.8	0.33	2.3	0.03
II	1	Sept. 22, 1937	21.5	0.51	3.62	12.1	0.35	1.6	.02
IV	10	Oct. 4, 1937	20.9	0.60	3.73	11.2	0.36	2.1	0.02
I	1	Oct. 21, 1938	18.9	0.43	3.50	12.1	0.50	2.0	0.05
II	1	Oct. 9, 1938	21.3	0.36	3.44	12.0	0.42	2.6	0.06
IV	4	Sept. 18, 1938	19.8	0.40	3.91	10.9	0.42	2.4	0.07
I	1	Sept. 9, 1939	20.5	0.53	2.96	10.0	0.42	2.3	0.01
I	2	Sept. 20, 1940	20.1	0.48	3.47	10.1	0.51	2.1	0.02
IV	1	Oct. 9, 1940	23.7	0.47	3.78	20.0†	0.29	7.0	0.04
Malaga									
IV	1	Oct. 24, 1936	21.8	0.41	3.87	11.4	0.35	2.6	0.03
IV	1	Oct. 22, 1937	17.0	.63	3.65	10.6	0.31	2.1	0.03
IV	1	Oct. 28, 1940	21.5	0.34	3.90	..	..	..	..

Flat; thin, but palatable; ordinary  
Delicate, pleasant flavor, very flat  
Slight aroma; lacks character and balance

Soft, slightly alcoholic; tends to spoil  
Thin, uninteresting, very flat; little character

Very light color, flavor, body; lacks acid  
Soft; lacks flavor and character; poor  
ordinary

Pleasant, early-maturing, flat; common  
Little flavor, mediocre quality

Little character, common flavor. Duplicate lots fermenting with added tartaric or citric acid were also  
ordinary

Slightly fruity, medium flavor, lacks acid

Very light color flavor, one sample more palatable  
Becomes amber; fair sweet-sherry material

Oxidized, flat; no character

Very flat, clean, but ordinary

Flat, with little flavor; mediocre quality

Almeria (Ohanz)

IV	2	Dec.	3, 1935	23.0	...	..	13.0	0.31	2.2	0.04	Very ordinary as table wine or sherry
IV	10	Nov.	6, 1936	19.7	..	..	12.8	.27	..	.04	Very poor; no character; ordinary sherry also
IV	12	Nov.	23, 1937	20.0	..	..	15.2†	.36	2.4	.03	Common-quality sherry
IV	17	Nov.	12, 1940	20.8	0.48	..	11.3	0.35	2.3	0.02	Clean; neutral; no character or flavor

Thompson Seedless

IV	3	Oct.	15, 1935	24.3	0.66	..	12.0	0.41	2.5	0.04	Flat; ordinary table wine; palatable sherry
IV	5	Oct.	12, 1937	25.1	.67	3.60	13.1	.38	2.5	.03	Neutral, flat table wine; fair sherry
IV	1	Nov.	3, 1938	25.1	.48	....	18.5†	.32	3.6	.04	Clean; soft; good-quality sherry material
IV	6	Oct.	16, 1940	26.2	0.48	3.72	19.3†	0.20	16.1	0.03	Clean, fruity; average Angelica

\* Determined in a color comparator using an arbitrary color standard made from Eastman ABC dyes; the color intensity increases as the figures increase.

† Fermentation arrested by the addition of grape brandy.

wines of these varieties appear in table 24. Only a few are presented, since the lack of sugar and acid is so obvious and so uniform.<sup>74</sup>

*Almeria*.—This variety is more correctly called Ohanez, but it has become established commercially as Almeria. It ripens very late, reaching harvesting maturity in late October or November. Since the clusters are loose, the pulp firm, and the skin thick and tough, the grapes ordinarily remain in good condition. The demand for shipping is usually satisfactory, and only culls are ordinarily received by the wineries. The Balling reading rarely exceeds 20° or 21°, and the acidity is very low. In the winery the grapes should be used—if at all—only for the production of distilling material.

*Chasselas doré*.—The Chasselas doré is the best known of the many Chasselas varieties in the state. A true Chasselas, it should not be confused with Palomino, which is called Golden Chasselas in Napa and the adjacent counties. Palomino is a totally different grape, adapted for sherry production—in no sense a Chasselas. (See p. 546.) The common Chasselas found in California is frequently called Sweetwater and Gutedel.

The Chasselas doré vines are small and only moderately productive. The clusters are medium-sized, long-conical, shouldered, and compactly set with medium-large, tender berries. With maturity the fruit softens and may be difficult to handle. Ripening early, it is attacked by deer in the foothill regions.

This is the leading table grape of France. There it is used very little for wine production except in certain northern districts, where its low acidity makes it useful for producing palatable wines. Before 1918 the Chasselas (Gentil) wines of Alsace were sometimes used in Germany to reduce the acidity of the Riesling wines. The Gutedel wines of Germany and the Fendant wines of Switzerland, made from this variety, are light and pleasant. But the areas in which Chasselas doré is used for wine making are among the coolest where the grape is grown, and nowhere, here or abroad, does it produce a quality wine. Here this variety never has enough acid for a satisfactory table wine. Even in region I, where the wines have been light, mildly delicate in aroma, and pleasantly flavored, they are flat. The warmer the region, the flatter and poorer the product.

One lot of wine handled to produce material for sweet sherry was fair, but became dark very early. Under California conditions—judging from the composition of the musts—this variety is best suited for dessert wine of average quality, but its low productivity would prevent it from competing with other acceptable varieties.

Hilgard's analyses showed very low acidity and only average wines. In 1907 Chasselas doré was not among the varieties recommended by Bioletti. On the basis of these and the present tests it is not recommended for California. It is not flavorful enough for quality wine nor productive enough for ordinary wines.

*Malaga*.—The Malaga is well known in region V in the San Joaquin Valley. Up to 1930 it was California's leading table grape. The fruit will not ripen normally in regions I, II, and III in the coastal counties.

The table wines have been flat, without character, and with little flavor. The

<sup>74</sup> Viticultural information on these varieties appears in: Jacob, H. E. Grape Growing in California. California Agr. Ext. Cir. 116:1-80. 1940.

variety is also of little use for dessert wines, since the products have been hard, coarse, and almost devoid of flavor or aroma.

The Malaga is and should continue to be a table grape of importance in certain limited areas. It should not be used for wine production, and the acreage should be reduced in favor of good white-wine varieties. When the grapes do reach the winery they should, if possible, be used for distilling material. If they must serve for wine, they are better adapted for sherry than for any other type.

*Thompson Seedless*.—This is California's most extensively planted grape variety, nearly 180,000 acres being in production. Although primarily a raisin grape, it is also extensively used for shipping. The fruit reaching the winery comes from packing-shed culls, grapes left on the vines as unsuitable for shipping, or, especially in years of low prices, the whole crop.

The fruit can withstand considerable handling without severe injury, since the berries are small and firm. It crushes only moderately easily and if pressed immediately has a juice yield below average. In actual practice, however, the free-run is usually taken off, and the pomace fermented with water for distilling material. Under these conditions the yields are better.

Thompson Seedless was tested by Hilgard and others for wine production, but the results were apparently discouraging; no recommendations were made by Hilgard or Bioletti.

Although the acidity is not so low as for other table-grape varieties, it is not high enough to produce sound table wines without amelioration. Even when acid is added and the best possible care taken during fermentation and storage, the resulting wines are neutral-flavored, almost devoid of character. Even when clean, they are very ordinary.

The only rational use for Thompson Seedless in the winery is for the production of distilling material and for sherry material. The neutral flavor is less of a handicap in sherry production; and the flavor after baking is soft, albeit neutral.

If the grapes are harvested very early, they are not unsuited as distilling material for beverage brandy.

#### RED AND BLACK TABLE-GRAPE VARIETIES

The red and black table-grape varieties commonly grown in California include Cornichon, Emperor, Flame Tokay, Hunisa, Red Malaga, and Ribier. Analyses appear in table 25.

*Cornichon*.—This variety has a rather thick skin but very juicy pulp, hence if handled in the same manner as other table-grape varieties will suffer proportionately more. The juice yield, however, is very good. The color of the skins is only sufficient, under region-IV conditions, to produce a pink wine even by fermenting on the skins for several days. White wines can be produced by early pressing, since the juice is colorless. The low sugar and acidity and the lack of flavor predispose the variety to use as distilling material only should it be delivered to the winery.

*Emperor*.—This very late-ripening variety reaches harvesting maturity in late October or November. The skins are so tough and the texture so solid as to withstand early rains fairly well; the grapes reach the winery in good condi-

TABLE 25  
COMPOSITION OF MUSTS AND WINES FROM BLACK AND FROM RED TABLE GRAPE

Region	Number of samples	Average harvest date and year	Must				Wine			
			Balling degrees	Total acid, grams per 100 cc	pH	Alcohol per cent	Fixed acid, grams per 100 cc	Extract, grams per 100 cc	Tannin, grams per 100 cc	Color intensity*
Cornichon (Olivette noir)										
IV	2	Nov. 22, 1935	19.8	0.48	9.8	0.30	1.7	0.03		Flat; tends to spoil as table wine; sherry also flat
IV	1	Oct. 21, 1936	18.0	31	4.00	10.7	30	1.9	03	Thin; very poor-quality pink wine
IV	3	Oct. 26, 1937	19.2	0.50	3.72	10.2	0.40	2.1	0.04	3Ry-3
Emperor										
IV	1	Nov. 20, 1935	20.0	0.50		11.3	0.32	2.7	0.03	Clean, flat; neutral character
IV	2	Oct. 23, 1940	19.2	0.51		10.1	0.40	2.3	0.04	Thin; very common quality
Flame Tokay										
IV	2	Oct. 21, 1935	18.9	0.37		9.7	0.34	1.9	0.03	Very thin; flat, lacks flavor and character
IV	2	Sept. 25, 1936	21.1	47	3.98	13.3†	34	2.4	16	Very flat; lacks character tends to spoil
IV	3	Oct. 9, 1937	19.1	47	3.69	10.8	40	2.1	03	Fat, clean, ordinary but not unpleasant
IV	1	Sept. 17, 1939	19.0	.52	3.35	9.5	44	1.8	0.01	Light, slightly fruity; drinkable, but flat
IV	1	Sept. 28, 1940	19.5	0.42	3.67	10.5	0.41	2.2		Slightly flat, average taste
Huasca										
IV	1	Oct. 29, 1940	18.1	0.50	3.63	9.5	0.40	2.0	0.04	Thin; flat; very common quality

Red Malaga (Molinera)									
IV	3	Nov. 16, 1935	23.6	0.53	...	12.1	0.33	2.6	0.05
IV	4	Oct. 25, 1937	21.8	4.7	3.74	12.0	.28	2.3	0.04
IV	1	Oct. 7, 1940	22.7	0.36	3.90	12.4	0.40	2.8	0.04
Ribier.									
IV	3	Nov. 1, 1935	20.2	0.55	-	10.8	0.34	2.5	0.08
IV	4	Oct. 13, 1937	17.6	50	3.58	9.5	35	2.1	0.06
IV	2	Oct. 10, 1940	19.0	0.52	3.77	9.9	0.46	-	3Ry-4
								3Ry-7	35
									Flat; poor; sherry; soft, but no character
									Flat, ordinary; tends to spoil
									No flavor; lacks arid; very poor quality

placed in right column, by one Dujacq-Sauveterre colorimeter; following Ruitard's procedure the observed figures have been divided into 4,000 so that the recorded figures will be proportional to the intensity. Data in right column, by use of color standards and a color comparator

tion. In view of their late ripening they seldom have a Balling reading of more than 20° or 21° and their acidity is very low. The wines have been ordinary even when the musts were acidified. Fermenting on the skins for several days gives only pale pink-colored wine. If delivered to the winery, Emperor should be used only for the production of distilling material.

*Flame Tokay.*<sup>7</sup>—The Flame Tokay, one of California's leading table grapes, appeals to the consumer because of its very delicate, brilliant, light-red color. In wine production, however, it is stripped of this most valuable property, since its wine must be made white. When fermented on the skins its wines have only a slight pink tinge, which has only a nuisance value.

The vines of Flame Tokay are very vigorous, eventually attaining enormous size. They are among the most productive of all vines. The clusters are very large, heavy, and conical, compactly set with very large ovoid-truncated berries. The variety grows well in all but the coolest and the hottest locations, but for producing the best table grapes the present acreage is chiefly in the Lodi area of region IV.

The table wines of this variety produced at Davis, and commercially, have been unsatisfactory. All were consistently flat, lacking in character, but clean and not unpleasant—that is, just ordinary wines. Their lack of acidity has been the primary but not the only deficiency.

The variety is less objectionable when used for dessert wines. Even so, its wines of these types are only average. Their main defects are a lack of character, a tendency to be sharp and coarse. They are surpassed by wines of other varieties such as Palomino, which is also a good producer. If Flame Tokay grapes are delivered to the winery, their best utilization is for distillation.

There should be no thought of expanding the acreage of Flame Tokay for wine making. The present (1942) surplus over the amount required for fresh consumption should be utilized primarily for distillation. If the surplus continues year after year, it should be eliminated by a shift to wine grapes of proved quality for the region.

*Hunisa.*—Only very small plantings of Hunisa are available in California. The fruit is large except that the variety frequently sets many small, seedless berries. The berries are firm, and the juice yield is small. Either white or pink wines can be produced. They are uniformly flat, oxidize easily, and lack alcohol. They should be used only in the production of distilling material.

*Red Malaga.*—This variety, also known as Molinera, ripens sufficiently for eating in midseason but will gain in sugar if left on the vines. The acidity is low, however, at 19° or 20° Balling; hence utility in the winery is restricted. The grapes are light red, but only pink wines can be produced by fermenting on the skins. White wines can be produced by pressing after crushing. The juice yield is below average. The grapes are of good quality until slightly after midseason, when they begin to rot. Should some of this variety have to be sent to the winery, it should be picked fairly early. Although it is better balanced for producing distilling material, an occasional sample harvested late in the season in years of dry, hot, ripening periods can be used for sherry material.

<sup>7</sup> This variety has no relation to the grape used for producing the natural sweet wine known as Tokay in Hungary. The variety used there is a white wine grape (see p. 657). Likewise the California wine type known as Tokay does not resemble the Hungarian wine. Ordinarily it is not even produced from the Flame Tokay grape and is a blended dessert wine.

Since, however, the flavor is rather neutral, such uses should be gradually eliminated.

*Ribier*.—This is the principal black table-grape variety in California. Its clusters are large-sized, conical, shouldered, well filled with very large black berries. The fruit handles and ships well. The variety is best adapted to warm locations. The juice yield is very good.

The musts of region IV were poorly suited for wine, being low in total acidity and sugar and with a relatively high pH. The table wines possessed no character or flavor and were flat and difficult to keep. The color was a particularly undesirable orange tint. Sherries produced by baking were no better than the dry wines, being too low in acid, flavor, and particularly in body.

This variety should not be employed for wine making. If the fruit arrives at the winery, it may go into distilling material.

#### ACKNOWLEDGMENTS

The authors wish to express their appreciation to the following companies and growers for their coöperation in securing the many lots of grapes: Almaden Vineyard, J. Arakelian, George Bear, Bear Creek Vineyard Association, Beaulieu Vineyards, Bedford Winery, George Barbero, George Borra, Mrs. Bridge, Carl Bundschu, California Grape Products Company, W. Cerps, Costa Brothers, F. Cribari and Sons, Cresta Blanca Wine Company, W. A. Dilley, The El Solyo Ranch, George Ferrara, E. Ferrario, Fountaingrove Vineyard, E. Fusaria, F. Garatti, S. Garberoglio, F. C. Gulla, A. Haentze, P. Hopper, Hopper Ranch, L. Iacopetti, Inglenook Vineyard Company, Italian Vineyard Company, Italian Swiss Colony, F. T. Kirschenmann, Korbel Bros., A. Kunde, S. La Fata, N. E. Leed, D. Leer, Lombardi Winery, Madera Winery, C. Mangels, L. K. Marshall, L. M. Martini Grape Products Company, A. Mattei Winery, Merkey Vineyard, P. L. Mirassou, E. Meyer, Mont La Salle Vineyards, R. E. Nelsen, L. Nerelli, Novitiate of Los Gatos, J. Ohrwall, J. Osborn, A. B. Parducci, E. W. Peterson, E. Piccioni, V. Pirone, J. Podesta, C. E. Quistorf, Martin E. Ray, The Riehr Vineyard, S. Riesland, H. L. Rixford, V. Rizzo, Roma Wine Company, Rusconi Bros., F. Salmina and Sons, C. Saroglia, Mrs. A. D. Seghesio, F. W. Silvear, W. Sink, Stanley Estate, U. S. Department of Agriculture Bureau of Plant Industry, E. Valliant, J. A. Verazzo, Wente Bros., W. Wildhagen.

Thanks are also due our colleagues for advice and consultation during the course of this investigation and for suggestions and criticisms in the preparation of this report.



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# H I L G A R D I A

A Journal of Agricultural Science Published by  
the California Agricultural Experiment Station

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Vol. 15

FEBRUARY, 1944

No. 7

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## ADDITION OF EXTRACTIVES OF ROTENONE-BEARING PLANTS TO SPRAY OILS<sup>1,2</sup>

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### INTRODUCTION

ALTHOUGH THE ADDITION OF EXTRACTIVES<sup>7</sup> OF rotenone-bearing plants to spray oils used against scale insects on citrus trees has long occupied the attention of entomologists (Ebeling, 1940),<sup>8</sup> it is only recently that oils to which toxicants have been added were used extensively in commercial practice in southern California. Commercial use of oils plus toxicants has had the effect of emphasizing practical problems such as (1) the possibility of dissolving adequate concentrations of extractives in spray oils without the use of a mutual solvent; (2) the passage of a toxicant from the oil to the water phase of an emulsion; (3) the effect of the different types of mutual solvents used to incorporate the extractives into the spray oil, on the physical nature and stability of the toxic solution and on the insecticidal effectiveness of the spray; (4) the effect of the mutual solvents on the oil-depositing properties of the spray; (5) decomposition of the toxicant during the varying periods between manufacture and use; (6) the relative value of rotenone, rotenone-free extractives, and total extractives of rotenone-bearing plants; and (7) the long-term effect on the scale population density resulting from the lighter oils which are made more effective by the addition of a toxicant, but which nevertheless do not leave a long-lasting film of oil on the tree to retard the development of the progeny of those scales which fail to succumb to the oil. The purpose of this paper is to evaluate the relative importance of these and other incidental factors and to suggest means by which present difficulties may be overcome.

### SOLUBILITY OF DERRIS OR CUBE EXTRACTIVES IN OIL

*Solubility of Derris or Cubé Extractives in Oil without the Aid of a Mutual Solvent.*—The prevailing preoccupation of entomologists with mutual solvents as a means of incorporating derris and cubé extractives into oil should not

<sup>1</sup> Received for publication April 10, 1943.

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<sup>7</sup> The total resinous material extracted from derris or cubé root by organic solvents and containing the insecticidal ingredients of the root.

<sup>8</sup> See "Literature Cited" at end of the paper for complete data on citations, which are referred to in the text by author and date of publication.

direct attention away from the fact that a considerable concentration of extractives can be dissolved directly in the oil even at room temperature. Two grams of derris extractives (35 per cent rotenone) which had been powdered and sieved through an 80-mesh screen was placed in each of two 500 ml flasks; 100 ml of light-medium straight oil<sup>19</sup> was added to one flask, and 100 ml of light-medium emulsive<sup>20</sup> oil was added to the other. Both flasks were then tightly corked and shaken by hand continuously and uniformly for 20 minutes at 25° C. The oils were then filtered through a Seitz pad (no. 6), and the concentration of rotenone plus deguelin in the filtrates was determined according to Gunther's modification of the Gross and Smith color test (Gunther and Turrell, 1944). The concentration of rotenone plus deguelin was 0.8 gram per liter in the straight oil, and 1.5 grams per liter in the emulsive oil.

The experiment was later repeated with derris extractives of a different origin, which had been extracted with a different solvent and contained only 30 per cent rotenone. Four grams of the powdered extractives (80-mesh) was added to 100 ml of straight oil and to 100 ml of emulsive oil, both in 500-ml flasks as before. The two flasks were placed in a shaking machine constructed for the purpose to obviate any possibility of error due to a difference in the degree of agitation of the liquid. The concentration of rotenone plus deguelin was 1 gram per liter in the straight oil, and 2 grams per liter in the emulsive oil. Still higher concentrations of extractives can be obtained by the use of heat.

The glyceryl dioleate in the emulsive oil made it possible in both tests to approximately double the amount of rotenone plus deguelin dissolved. Glyceryl dioleate is surface-active, as is shown by the fact that it lowers interfacial tension, and it is a good solvent for derris or cubé extractives, so that at the interface between the oil and the resin particle it apparently acts as a solvent or solubilizer to bring the rotenone plus deguelin more rapidly into solution in the oil. English (1939) greatly increased the efficiency of an oil-derris mixture when he used diglycol oleate as an emulsifier, but he used this solute at such a high concentration in the oil (10 per cent) that the solute itself might have been the carrier of the toxic ingredients of the derris powder.

It is interesting to note, as will be shown presently, that, in the case of the straight oil, about as high a concentration of rotenone plus deguelin can be obtained by soaking finely ground cubé root in the oil as was obtained by soaking the extractives in oil, and this concentration can be obtained in just as short a period as when the total derris extractives are dissolved. It should be borne in mind, however, that the extractives were from different plants; *Derris* in one case and *Lonchocarpus* in the other.

To determine the amount of rotenone plus deguelin that can be dissolved in oil from cubé root (5 per cent rotenone) ground so that not less than 95 per cent passed through a 200-mesh screen, various amounts of the ground root ranging from  $\frac{1}{2}$  to 12 grams were added to 100-ml portions of light-medium spray oil in 500-ml flasks. The flasks were then continuously shaken by hand in a uniform manner, as before, for 20-minute periods at 25° C. The oil was

<sup>19</sup> Fifty-six per cent distilled at 636° F.; viscosity, 70 seconds Saybolt at 100° F.; unsaponifiable residue 90 per cent. A straight oil is one to which no solute has been added.

<sup>20</sup> An emulsive spray oil is one which contains usually about 1 per cent of an oil-soluble emulsifier, which greatly reduces the interfacial tension between oil and water. The emulsive oil used in the experiments presented in this paper contained 1 per cent glyceryl dioleate.

then filtered through a Seitz pad (no. 6) and the concentration of rotenone plus deguelin in the filtrate was determined in the same manner as for the previous filtrate. The concentrations of rotenone plus deguelin in the filtrates are shown in figure 1. Curve *B* shows the increase in concentration of rotenone plus deguelin with increasing amounts of cubé root added to straight light-medium oil, and it also shows the decreasing rate of solution.

Curve *A* in figure 1 indicates the far greater efficiency obtained in the extraction of rotenone plus deguelin from ground cubé root if emulsive spray oil

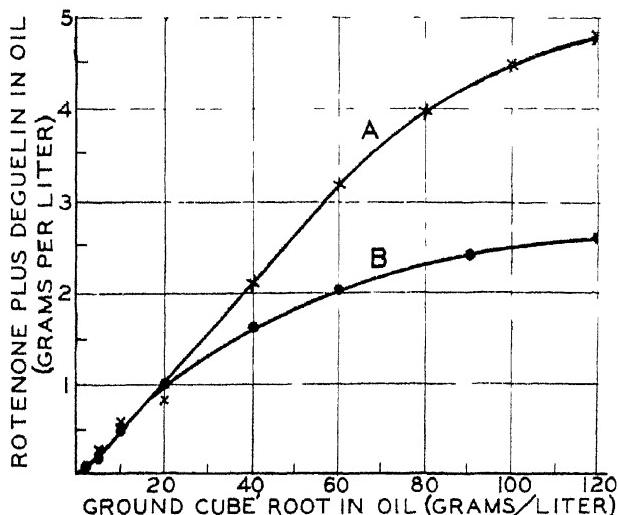


Fig. 1. -- The increase in the amount of rotenone plus deguelin extracted from various amounts of finely ground cubé root (5 per cent rotenone) shaken in 100-ml portions of emulsive and straight spray oils for 20-minute periods. *A*, Emulsive oil; *B*, straight oil.

is used as the solvent when the amount of the ground root is greater than 20 grams per liter of oil. The superiority of the emulsive oil above this point becomes relatively greater as the proportion of the ground root is increased; when 120 grams of ground root per liter is used the emulsive oil is almost twice as effective a solvent as the straight oil. The two oils are identical except for the 1 per cent glyceryl dioleate in the emulsive oil.

The experiment was repeated, but with a cubé root of a lower rotenone-plus-deguelin content. This time the flasks containing the oil and ground root were shaken together on a shaking machine for 20 minutes. Although the amount of rotenone plus deguelin dissolved by the oil was lower than in the previous experiment, the superiority of the emulsive oil in extracting these compounds was just as great as before.

In two separate tests, when 40 and 60 grams of ground cubé root were shaken in a shaking machine in 1 liter of emulsive oil for 1 hour, the amount of rotenone plus deguelin extracted was no greater than when the same amount of root was shaken in the oil for only 20 minutes.

Emulsive oils would probably differ in their solvent properties according to

the nature of the solute they contain. Likewise the nature of the ground root would also have an effect on the amount of rotenone plus deguelin dissolved by the oil. In the present investigation the ground root of *Derris* containing 6 per cent rotenone and ground to a 200-mesh-particle size was shaken in emulsive oil for 20-minute periods in order to compare the amount of rotenone plus deguelin extracted by emulsive oil from derris root with that which had been extracted from cubé root (*Lonchocarpus*) containing 5 per cent rotenone under identical conditions. The derris root was added to the emulsive oil at the rate of 20, 40, 80, and 120 grams per liter. The average concentration of rotenone plus deguelin in the oil was 36.2 per cent less than that which resulted from the extraction of the same amounts of cubé root.

In comparing the solubility in oil of the rotenone plus deguelin as contained in the total derris extractives and as it exists in its natural state in the ground cubé root, it should be borne in mind that the root particles were on the average probably more finely divided than the particles of derris extractives, since 95 per cent of the ground root particles would pass through a 200-mesh screen, while the powdered derris extractives were sieved through an 80-mesh screen. However, since probably not more than 10 per cent of the ground root material will respond to the Gross and Smith color test as compared with at least 60 per cent of the derris extractives, it is remarkable that the rotenone plus deguelin can be so easily extracted from the ground root. In the case of the straight oil, a higher concentration of the rotenone plus deguelin was obtained in 20 minutes from 2 grams of ground root than from 2 grams of the powdered derris extractives. This may be explained by investigations of derris root made by Gunther and Turrell (1944), who showed that the whole derris extractives were present in the root as a colloidal suspension of particles ranging in size from  $0.77\mu$  to  $3.85\mu$  in diameter, and were concentrated in parenchymatous extractive-bearing cells, which may be more completely disintegrated in the grinding process than the rest of the root cells. These particles of extractives as they occur in nature are extremely small in comparison with those resulting from powdering of the total extractives with mortar and pestle, which may account for the ease with which they may be dissolved. The over-all effect of the grinding of derris root is that each particle of ground root (cellulose and extraneous matter) becomes coated with a thin film of the much smaller particles of whole derris extractives. Rapidity of solution is an inverse function of particle size.

However, it has long been recognized that the maximum concentration of derris or cubé extractives in oil may, for practical purposes, be best obtained by means of mutual solvents. The latter may be divided into two groups: solubilizers and oleotropic solvents.

**True Solubilizers.**—Some mutual solvents form a colloidal solution of the extractives in the oil, and these will be referred to as *solubilizers*, their effect being different from that of the mutual solvents which form molecular solutions. The term "solubilizer" may be found in entomological literature as referring to a solvent of any type which can bring into solution in oil a substance ordinarily not oil-soluble. However, McBain and his associates (1941) have considered solubilization as referring only to the preparation of thermodynamically stable colloidal solutions by the addition of otherwise insoluble

materials to dilute aqueous or nonaqueous solutions of detergents. They state, "We may venture the conclusion that it is possible to solubilize almost any material in almost any solvent, as desired. A good solubilizer should be effective in concentrations of 1 per cent or less."

These authors (1941) distinguished between solubilization and the change in solvent power when large quantities of a second solvent are added to a liquid which is by itself a poor solvent. They also show the difference between solubilization and emulsification, suspension, or peptization. Further, they cite the X-ray evidence of Kiessig and Philippoff (1939) on the nature of the lamellar micelles enclosing benzene solubilized in sodium oleate solutions; and they contribute three other distinct types of experimental evidence, produced in their own laboratories, to support the conclusion that solubilization consists in the spontaneous stable formation of self-organized colloidal particles.

To demonstrate the colloidal nature of toxic solutions containing Cardolite<sup>11</sup> as a solubilizer, test tubes were filled with unit quantities of a light-medium spray oil containing various concentrations of the standard Cardolite-extractives-oil stock solution (see footnote 11). A 250-watt, 12-volt electric light bulb was enclosed in a box with an 11-inch square base and 13 inches high, which was lined on the inside with tin foil. A  $\frac{3}{8}$ -inch circular hole was drilled into the top of the box directly above the light bulb, in order that a beam of light might be cast upward from the box into a dark room. The test tubes containing the solutions were placed in a vertical position above the hole. The light from the bulb passed through the center of the column of liquid, producing a Tyndall effect which proved the presence of discrete particles in the solution. The liquid surrounding the beam of light was also somewhat luminous. If oil alone is examined in the above manner, it will be found to show only a faint path of bluish fluorescence.

An attempt was made to determine whether rotenone alone would form a colloidal solution when dissolved in Cardolite at a concentration of 16½ per cent and added to spray oil. However, the Cardolite would dissolve not more than 4 per cent of rotenone, and when this solution was diluted with oil in any proportion, one was formed which showed no Tyndall effect. This was also true when only 4 per cent total derris extractives was dissolved in the Cardolite. It may be that the rotenone in an oil-Cardolite-extractives solution is in true solution and that the colloidal particles are made up of the remaining rotenone-free extractives. However, if only 4 per cent of rotenone or total extractives were dissolved in the Cardolite in the preparation of a stock solution, too much of the latter would have to be added to the oil in order to obtain an adequate concentration of the toxicant to substantially increase its effectiveness in

<sup>11</sup> Cardolite 627 is a condensation polymer of formaldehyde and the phenolic constituents of cashew-nut-shell oil (cardanol). A stock solution was prepared which consisted of 4.16 per cent derris extractives (30 per cent rotenone), 20.84 per cent Cardolite 627, and 75 per cent light-medium oil; all percentages by weight. The solution contains 1.25 per cent, by weight, of rotenone. The derris extract is added to the Cardolite at a temperature of 125° C and is dissolved in 1 or 2 minutes, then immediately further diluted with oil to reduce the temperature of the solution below that which is considered detrimental to rotenone.

At the time of this investigation the writers knew of no method for the determination of rotenone in solutions containing Cardolite. Therefore, a method was devised which involved a chromatographic treatment of the toxic solution in order that rotenone might be separated and subsequently determined colorimetrically (Gunther, 1942).

citrus-pest control. Such high concentrations of Cardolite in the oil adversely affect emulsification in the spray tank.

When Cardolite-extractives-oil solutions containing a concentration of rotenone plus deguelin of from 0.04 to 0.20 gram per 100 ml are filtered through a Seitz pad (no. 6) their concentrations of rotenone plus deguelin may be reduced as much as 50 per cent, many of the larger colloidal particles being removed. The luminosity of the path of light passing through a column of the filtrate is much less than that observed in the unfiltered solution, and the liquid surrounding the path of light is nearly "optically void," having largely lost the luminosity observable in unfiltered solutions. A filtrate with a concentration of 0.12 gram per 100 ml of rotenone plus deguelin was found to show less Tyndall effect than an unfiltered solution with a concentration of rotenone plus deguelin of only 0.04 gram per 100 ml. This again indicates that a portion of the extractives in the Cardolite-extractives-oil solution is in molecular solution.

*Oleotropic Solvents.*—A different type of solution is obtained when solvents not having the ability to solubilize are added in large quantities to a less effective solvent, with the result that the mixture will dissolve substances which would otherwise not go into solution. This is a far less efficient method of getting a substance into solution than is solubilization. A large quantity of a good solvent is necessary in order to make a poor solvent effective; and conversely a small amount of poor solvent will spoil a good solvent. However, if a solution is obtained it is a molecular solution rather than one predominantly colloidal, such as is obtained by solubilization.

Neuberg (1916) proposed the name "hydrotropic" for solvents which, when added to water in large amounts, will increase the solubility of a substance not ordinarily water-soluble. Twenty five per cent or more of the hydrotropic solvent is ordinarily added. The term "hydrotropic" would be a misnomer when applied to solvents added to oil. The writers therefore propose the term *oleotropic* as descriptive of solvents other than solubilizers that may be added to oil to increase its ability to dissolve substances ordinarily insoluble in oil.

The oleotropic solvents which have been tried at this station with more or less success were for the most part esters, ketones, and a complex hydroxy ether, 2 (4-tertiary butylphenoxy) ethanol. When 5 per cent derris extractives (30 per cent rotenone) is dissolved in *n*-butyl phthalate, 1 part of the resulting solution must be added to 2 parts of spray oil in order to obtain a clear solution of the extractives. The same concentration of derris extractives dissolved in diamyl phenol may be diluted 1 to 20 in spray oil and still result in a clear solution. Diamyl phenol is the most effective oleotropic solvent the present writers have investigated, but unfortunately it is somewhat injurious to citrus foliage. A 10 per cent solution of derris extractives in 2 (4-tertiary butylphenoxy) ethanol resulted in a slightly cloudy solution at the dilution of 1 part to 7 parts of oil, but formed a clear solution at higher concentrations in the oil. Using Cardolite as a solubilizer, however, a 16½ per cent solution of derris extractives has been diluted in the ratio of 1 part to 156 parts of oil in commercial spraying practice; it can be diluted much more than this and still maintain a visually clear colloidal solution, which, however, shows a Tyndall effect at any concentration in the oil.

## PASSAGE OF THE TOXICANT FROM THE OIL TO THE WATER PHASE OF AN EMULSION

*Theoretical Considerations.*—The possibility of the loss of toxicity due to the passage of derris or cubé extractives from the oil to the water phase of a spray mixture has been a matter of concern among those working with oil-toxicant sprays. A theoretical consideration of the problem, however, indicates that loss of toxicity from this source could, at the most, be only extremely small if the extractives are in true monomolecular solution in the oil.

When a substance has reached an equilibrium between two immiscible solvents the ratio of the concentrations in the two phases will have a constant value at a given temperature:

$$\frac{C_1}{C_2} = K \quad (1)$$

When a petroleum oil solution containing rotenone is agitated with water, the rotenone passes into the aqueous phase until the equilibrium ratio characteristic of the substances in question is established. When the solute is sparingly soluble, as in the system under consideration, this ratio is identical with the ratio of the solubilities of the substance in each solvent. If there are several solutes in solution, the distribution of each is the same as if it were present alone. A more formal treatment of this principle leads to the equation (Robertson, 1938) :

$$x = \frac{K v_1 a}{v_2 + K v_1} \quad (2)$$

when  $x$  is the weight of rotenone passing from the oil to the water,  $K$  is the equilibrium ratio and is equal to  $\frac{S_1}{S_2}$  when  $S_1$  is the solubility of the rotenone in the water and  $S_2$  is the solubility of the rotenone in the oil,  $a$  is the original weight of rotenone,  $v_1$  is the volume of water, and  $v_2$  is the volume of petroleum oil. This equation is applicable to the system under consideration because of the extremely small percentages of the solutes involved.

Frrear (1942) states that the solubility of rotenone in water is about 160 micrograms per liter at 25° C. The present writers, by adding a large excess of powdered rotenone to light-medium spray oil at 100° C and keeping the oil, at this temperature, stirred for 10 hours by means of an electric mixer, then cooling to 25° C, found the solubility of rotenone in the oil to be about 1.6 grams per liter at 25° C.

Converting these solubilities to the same units, at 25° C,

$$K = \frac{S_1}{S_2} = 1 \times 10^{-4}.$$

Assume that 1 gram of rotenone is dissolved in 1 liter of the oil and that the resulting solution is mixed with 49 liters of water at 25° C, as in a 2 per cent oil-toxicant spray, until equilibrium has been attained. In order to determine

the weight of rotenone ( $x$ ) which has entered the aqueous phase, the appropriate values are substituted into formula 2:

$$x = \frac{(10^{-4})(49)(1)}{(1) + (10^{-4})(49)} = 4.8 \times 10^{-3} \text{ gram of rotenone in the 49 liters of aqueous phase.}$$

Thus 0.48 per cent of the original quantity of rotenone dissolved in the oil has been transferred from that phase to the aqueous phase.

*Experimental Results.*—It can be seen from the above calculation that theoretically, when dealing with the very dilute solutions of field practice, the amount of rotenone leaving the oil and entering the water phase of an emulsion as a solute is of no practical importance. Experimental evidence substantiated this conclusion. Derris extractives containing 35 per cent rotenone were dissolved in light-medium oil with the aid of heat. A 1 3/4 per cent concentration of the toxic oil was agitated in 5 gallons of water in a 10-gallon-capacity spray tank for 45 minutes. A part of the spray mixture was then sprayed into a liter graduate, and a gram of powdered calcium chloride was added to the spray mixture to aid in the separation of the oil and water. In 5 minutes the oil which had risen to the surface was transferred to a test tube and centrifuged for 15 minutes to separate the oil completely from the small amount of residual water. A portion of the original oil sample which had not been mixed with the water also was centrifuged. According to an analysis for rotenone plus deguelin made by means of Gunther's modification of the Gross and Smith color test, the oil which had not been mixed with water had a concentration of rotenone plus deguelin of 0.0080 gram per 100 ml, while the oil which had been vigorously agitated with water for 45 minutes had a concentration of rotenone plus deguelin of 0.0079 gram per 100 ml, which did not indicate a significant loss of the toxicant from the oil phase. Under identical conditions an emulsive oil solution containing a concentration of rotenone plus deguelin of 0.20 gram per 100 ml of oil had this concentration reduced to 0.19 gram per 100 ml of oil by agitation with water for 45 minutes; this again indicates a very small loss, if any, of the rotenone plus deguelin to the water phase of the spray mixture.

A test which was performed in the same way, but in which the toxic oil contained 1 part of a Cardolite-derris-extractives-oil solution (see footnote 11) to 19 parts of light-medium spray oil, revealed a loss of about 25 per cent of the rotenone plus deguelin from the oil phase of the spray mixture. It is not known what proportion of the extractives lost was rotenone and what proportion was deguelin. From a concentration of rotenone plus deguelin of 0.04 gram per 100 ml in the original oil, the concentration was reduced to 0.03 gram per 100 ml. In another experiment with the Cardolite-extractives-oil solution, the reduction in concentration of rotenone plus deguelin due to a 45-minute agitation with water was from 0.72 gram per 100 ml to 0.48 gram per 100 ml, representing a loss of one third of the toxicant.

It appears that although rotenone and deguelin in molecular solution in oil do not pass from the oil to the water phase to any appreciable extent, a solution which is largely colloidal may lose as much as a third of its content of toxic ingredients which respond to the Gross and Smith test, probably by particle exchange.

## EFFECT OF THE MUTUAL SOLVENT ON OIL DEPOSIT AND ON THE INSECTICIDAL PROPERTIES OF THE TOXIC SOLUTION

Despite the greater efficiency of Cardolite as a mutual solvent, extensive investigation has indicated that the oleotropic solvents are usually more effective as far as insecticidal properties of the oil-toxicant solution in which they are contained are concerned (Ebeling, 1940). However, when very low concentrations of derris or cubé extractives are sufficient for the required insecticidal effect, as in the kerosene-toxicant sprays to be described in this paper, Cardolite appears to be the best and most practical mutual solvent of all those which the writers were able to test.

Smith (1932) seems to have been the first to use *n*-butyl phthalate as a mutual solvent in the preparation of oil-rotenone solutions. The high degree of effectiveness of oils containing derris extractives with *n*-butyl phthalate as an oleotropic solvent was shown in field experiments made at this station several years ago (Ebeling, 1940). Two per cent medium tank-mix oil spray resulted in a 21.2 per cent survival of adult female California red scale on the branches of lemon trees, and a 14.4 per cent survival on the fruit. When 1 part of *n*-butyl phthalate containing 5 per cent derris extractives (34 per cent rotenone) was added to 7 parts of medium oil and this oil-toxicant solution was used at 2 per cent, the per cent survival on the branches and fruit was, respectively, 3.9 per cent and 2.5 per cent (Ebeling, 1940).

Cressman (1941) also demonstrated the high degree of effectiveness against red scale of toxic solutions of cubé extractives (30 per cent rotenone) in oil with *n*-butyl phthalate as the mutual solvent. He stated, however, that a *n*-butyl phthalate-trichloroethylene mixture was more efficient as a solvent than *n*-butyl phthalate alone.

When Cardolite 627 was first tried as a means of incorporating derris or cubé extractives into spray oil, high hopes were held for the material because of its extreme efficiency; less than  $\frac{1}{2}$  per cent concentration of the solubilizer in oil was sufficient for the solubilization of practical quantities of derris extractives. Inspection of the three-component phase diagrams worked out by Kagy and Boyce (1941) shows that Cardolite was the only solvent which could bring any appreciable amount of derris extractives into solution in oil at concentrations of less than 5 per cent of solvent. However, some solvents were more efficient than Cardolite at higher concentrations of solvent. This may be explained by the fact that true solubilization requires only very small amounts of the solubilizer, and that which is added above this critical amount is superfluous and will not result in correspondingly greater incorporation of the extractives in the oil.

Combined with this high degree of solubilizing efficiency was the added incentive to the use of Cardolite caused by the fact that no other solvent could be used successfully with kerosene; such high concentrations of the kerosene were used in citrus spraying that oleotropic solvents would have been impractical, as well as being injurious to foliage, because of the large quantities which would have been necessary to bring about a solution of the extractives in the kerosene. Moreover, the kerosene-toxicant solutions, using Cardolite as a solubilizer, were highly effective against the red scale when freshly prepared solutions were used at a 10 per cent concentration (Ebeling, 1941).

A factor which excludes from consideration some otherwise excellent mutual solvents is excessive emulsifying ability of the solvent or excessive spreading of the spray mixture caused by the solvent. This results in too greatly reduced oil deposit with a consequent reduction in the effectiveness of the oil spray which may outweigh the advantages gained from the introduction of an effec-

TABLE 1

DIFFERENCE IN EFFECTIVENESS AGAINST CALIFORNIA RED SCALE OF SPRAYS CONTAINING SOLUTIONS OF DERRIS OR CUBÉ EXTRACTIVES IN LIGHT-MEDIUM EMULSIVE SPRAY OIL, USING OLEOTROPIC SOLVENTS, A SOLUBILIZER, AND NO MUTUAL SOLVENT\*

Treatment no.	Material	Concentration of extractives in the oil (per cent by weight)†	Oil deposit on leaves (ml/cm <sup>2</sup> ·10 <sup>6</sup> )		Net per cent survival‡	
			Orchard A	Orchard B	Orchard A	Orchard B
1	Oil without toxicant . . . . .	.	100.3	102.3	25.1	40.2
2	Oleotropic solvent: <i>n</i> -butyl phthalate with 5 per cent derris extractives, 1 part to 15 parts of oil . . . . .	0.31	.	85.8	....	0.1
3	Oleotropic solvent: <i>n</i> -butyl phthalate with 5 per cent derris extractives, 1 part to 7 parts of oil . . . . .	0.62	68.7	79.3	5.6	0.9
4	Oleotropic solvent: <i>n</i> -butyl phthalate with 10 per cent derris extractives, 1 part to 15 parts of oil . . . . .	0.62	62.6	..	19.2	.
5	Oleotropic solvent: diethyl phenol with 10 per cent derris extractives, 1 part to 15 parts of oil . . . . .	0.62	.	85.0	..	2.3
6	Solubilizer: oil-Cardolite with 4.18 per cent derris extractive, 1 part to 15 parts of oil . . . . .	0.26	78.3	93.8	20.3	0.9
7	Solubilizer: oil-Cardolite with 4.18 per cent derris extractives, 1 part to 7 parts of oil. . . . .	0.52	76.2	....	24.6	....
8	No mutual solvent: ground cubé root, 4 ounces to 1 gallon of oil. . . . .	0.14	78.5	83.4	0.0	8.8
	Least significant difference for odds of 19 to 1	....	....	..	8.4	8.3

\* The oil used was 54 per cent distilled at 133° F; viscosity, 89 seconds Saybolt at 100° F; unsulfonatable residue, 90 per cent. In all treatments the oil or oil-toxicant was used at 2 per cent concentration. The treatments in orchard A were made on April 9, 1942, and those in orchard B were made on July 6, 1942, and in each grove the scales were examined about 6 weeks after treatment.

† The percentages of extractives in this and following tables are calculated, except in treatments in which the ground cubé root was soaked in the oil. In the latter the values were determined by analysis and do not show the per cent of extractives other than rotenone and deguelin.

‡ From 4,384 to 5,783 adult female red scales were examined for each treatment. In the entire experiment 30,593 insects were examined. Variation between trees was determined in each plot and subsequently pooled over all plots. This served to provide a standard error for mean values of each plot, hence for standard errors of difference between any two plots. From this the least significant difference as based on Fisher's *t* test was calculated.

tive toxicant. An example of such a solvent is 2 (4-tertiary butylphenoxy) ethanol, which was one of the most efficient of the oleotropic solvents tested, yet has such great emulsifying and spreading properties that it cannot be successfully used against insects requiring a heavy oil deposit for successful control, such as the red scale. Against other scales, such as the black scale, *Aonidiella aurantii* (Bernard), the successful control of which does not require a heavy film of oil, if the oil is sufficiently toxic, the 2 (4-tertiary butylphenoxy) ethanol can be used very successfully (Boyce and associates, 1940).

*Effectiveness of Different Solvents Containing Different Mutual Solvents.* To further test the greater insecticidal effectiveness of oleotropic solutions containing oleotropic solvents as compared with those containing

true solubilizers, some field experiments were designed to make possible a direct comparison of the two types of solvents within a single orchard. In one experiment (table 1, orchard A) the sprays were applied to an orange orchard and in the other (table 1, orchard B) they were applied to a lemon orchard, both orchards being heavily infested with California red scale. The sprays were applied with a high-pressure power sprayer with  $\frac{3}{4}$ -inch disks in the nozzles and with a degree of thoroughness comparable to the average commercial work in citrus spraying in southern California.

From 5 to 6 weeks after treatment the adult scales were examined *in situ* to determine the percentage surviving treatment. The interim between spraying and examination was sufficient to insure the death of those insects not immediately killed by the spray and to permit the complete desiccation of the dead scale to facilitate accurate and rapid determination as to whether the scales were alive or dead.

In each plot, 10 trees were examined and on each of these trees the number of insects on 20 units of branches (a unit consisting of from 4 to 6 inches of the branch as seen from one aspect) were recorded, together with the number alive. An average of about 6,000 scales per plot were counted. The net per cent survival was determined by dividing the percentage found alive in the treated plots by the percentage found alive on 10 untreated trees, examined at the time the counts were made on the treated plots, and multiplying the quotient by 100. Separate tabulations of the net per cent survival were made for each tree so that an estimate could be made of the error within plots.

Immediately after spraying, 100 orange leaves or 75 lemon leaves were picked and placed in quart jars to be later subjected to a steam-distillation treatment (Gunther and Ebeling, 1942) for the determination of the amount of oil applied per unit of leaf surface. The oil deposit per square centimeter is shown in tables 1, 2, 3, and 4.

Table 1 shows the great difference in insecticidal effectiveness of a given concentration of derris extractives in emulsive spray oil depending on the kind of mutual solvent used. Although in this particular experiment the concentration of derris extractives in the Cardolite solutions was a little less than in the *n* butyl phthalate solutions (0.26 and 0.52 per cent by weight as compared with 0.31 and 0.62 per cent in the latter), it has been shown (Ebeling and LaDue, 1948) that if the concentration of derris extractives is twice that shown in table 1, with a corresponding increase in Cardolite, the effectiveness of the oil spray is not significantly increased. Perhaps this is because straight oil will not emulsify properly if too much Cardolite is added. When emulsive oils are used, however, this difficulty is overcome, but the insecticidal effectiveness of the oil is still not improved by increased concentrations of the Cardolite-extractives solution.

Table 2 shows the results of an experiment in a lemon orchard on August 26 and 27, 1942, in which the Cardolite-extractives solution was used with both emulsive and straight oil of the light-medium grade. Although there was a substantial improvement in kill due to the toxicant when straight oil was used, there was no improvement with emulsive oil, even though the same concentration of toxicant was the same in each treatment.

It will be noted (table 1, orchard A) that when an *n*-butyl phthalate partial

solution containing 5 per cent derris extractives was used at 1 part to 7 parts of oil, the concentration of extractives was the same as when 10 per cent derris extractives was used at 1 part to 15 parts of oil, yet the former resulted in significantly better kill of red scale. The superiority of the 5 per cent partial solution is apparently due to the greater degree of solution; the liquid was only slightly cloudy as compared with the very cloudy appearance of the 10

TABLE 2

THE EFFECTIVENESS OF DERRIS EXTRACTIVES IN SPRAY OIL AS SHOWN BY TWO IDENTICAL SERIES OF EXPERIMENTS IN A LEMON ORCHARD\*

Treatment no	Material	Extractives in oil (per cent by weight)	Oil deposit on leaves (ml/cm <sup>2</sup> ) <sup>10<sup>6</sup></sup>	Net per cent survival†	
				Series A	Series B
1	Heavy-medium emulsive oil .. . . .	....	97.9	41.4	40.4
2	Light-medium emulsive oil .. . . .	....	90.8	46.0	50.4
3	Light-medium emulsive oil; oil-Cardolite with 4.16 per cent extractives, 1 part to 13 parts of oil .. . .	0.31	107.9	41.0	39.4
4	Light-medium straight oil; oil-Cardolite with 4.16 per cent extractives, 1 part to 13 parts of oil .. . .	0.31	105.9	23.3	26.2
5	Light-medium straight oil; oil-Cardolite with 4.16 per cent extractives, 2 parts to 13 parts of oil .. . .	0.62	109.6	26.2	25.9
6	Light-medium emulsive oil; n-butyl phthalate with 5 per cent extractives, 1 part to 7 parts of oil .. . .	0.62	81.6	16.5	15.2
7	Same as no. 6 except that the n-butyl phthalate-extractives solution was 54 days old .. . .	0.62	70.5	15.5	20.2
8	Light-medium emulsive oil, n-butyl phthalate with 3.75 per cent extractives, 1 part to 7 parts of oil .. . .	0.46	75.7	19.0	27.1
9	Light-medium emulsive oil; n-butyl phthalate with 5 per cent extractives, 1 part to 15 parts of oil .. . .	0.31	80.8	31.2	34.2
10	Light-medium emulsive oil, ground cubé root, 1 pound to 2 gallons of oil .. . . . .	0.12	83.9	17.5	25.6
11	Light-medium emulsive oil; ground cubé root, 1 pound to 2 gallons of oil .. . . . .	0.17	86.2	17.9	24.9
12	Light-medium emulsive oil; 1 n-butyl phthalate with 5 per cent extractives, 1 part to 7 parts of oil .. . .	0.62	63.6	50.1	51.4
Least significant difference for odds of 19 to 1.				10.1	9.5

\* The plots in series A were treated August 26, and those in series B, August 27, 1942. All oils or oil toxicants were used at 2 per cent concentration except in treatment 12, in which 1.5 per cent was used.

† From 4,954 to 6,602 adult female red scales were examined in each plot. The entire experiment involved the examination of 129,881 scales. Variation between trees was determined in each plot and subsequently pooled for all plots. This served to provide a standard error for mean values of each plot, hence for standard errors of difference between any two plots. From this the least significant difference as based on Fisher's *t* test was calculated.

‡ The oil toxicant in plot 12 was used at 1.5 per cent concentration in the spray mixture.

per cent partial solution when the two were added to the spray oil. Apparently, with any given mutual solvent, the greater the per cent of extractives actually in solution, the greater the insecticidal efficiency of the toxic solution. Presumably the suspended material does not readily penetrate the armor or body wall of the scale.

It can be seen from table 1, orchard B, treatment 5, that diamyl phenol may be successfully used as an oletropic solvent. This is in accord with the investigations of Kagy and Boyce (1941), who found diamyl phenol to be more effective as a mutual solvent, on the basis of plait-point determinations, than n-butyl phthalate. Unfortunately, some injury to citrus foliage results from the use of diamyl phenol.

The entire series of treatments listed in table 2 was repeated in the same orchard in order to determine how closely the net percentages of survival in the various plots would coincide in the two series of tests. These are recorded in the table as series A and series B. Although in this experiment a considerable percentage of insects survived in all the treatments, it should be borne in mind that the effectiveness of an oil spray is in part due to its residual effect in inhibiting the settling of "crawlers" produced by those scales which do not succumb to the spray treatment. The final insecticidal effectiveness of an oil spray is therefore greater than that which is indicated by per cent kill.

Again the oil toxicant containing a calculated concentration of derris extractives of 0.625 per cent (table 2, treatments 6 and 7) was found to be the most effective spray oil despite the lowering of oil deposit on the leaf surfaces due to the presence of the *n*-butyl phthalate in the spray mixture. However, in series A the oil containing ground cubé root (treatments 10 and 11) was not significantly inferior even though there was a much lower concentration of extractives in the oil. Treatment 7 shows that a 54-day period did not result in a significant reduction in the effectiveness of the *n*-butyl phthalate-extractives solution, as indicated by the percentages of survival for this treatment in both series of tests.

As in table 1, treatment 8, the finely ground cubé root (200-mesh, and containing 5 per cent rotenone) was stirred in the oil for about a minute; then the mixture was allowed to settle for about 20 minutes—the minimum period required to empty the average 400-gallon spray rig.

In both table 1 and table 2 it can be seen that although the cubé root did not result on the average in so great an improvement in the spray oil as that which resulted from a 5 per cent concentration of derris extractives in *n*-butyl phthalate used at a strength of 1 part to 7 parts of oil, its effectiveness per unit of extractives in the oil was considerably greater. The explanation probably is the fact that the extractives incorporated into the oil by means of *n*-butyl phthalate are partly in suspension, while those extracted by the oil are entirely in solution. If the ground root had been agitated in the oil in the same manner as the samples represented in figure 1, the percentages of rotenone plus deguelin in the oil would have been 0.15 per cent in treatment 10, and 0.32 per cent in treatment 11 (table 2), according to curve A in figure 1. The fact that the percentages were actually much lower (0.12 per cent and 0.17 per cent, respectively) indicates that the field method of mixing the root used in treatments 10 and 11 should be improved in order to bring about better extraction of the toxic ingredients.

To determine to what extent the extraction of rotenone plus deguelin from cubé root can be improved by proper mixing, the equivalent of 1 pound of ground cubé root (5 per cent rotenone) in 2 gallons of light-medium emulsive oil was stirred in a beaker for 1 minute and allowed to stand for 19 minutes. The concentration of rotenone plus deguelin in the oil, at the end of the 20-minute period, was 0.19 per cent by weight. When the ground root and oil were stirred violently with an electric mixer for 1 minute and allowed to stand 19 minutes, the concentration of rotenone plus deguelin in the oil was 0.25 per cent. When the ground root and oil were stirred to a froth by means of an electric mixer for 20 minutes, the concentration of rotenone plus deguelin in

the oil was 0.35 per cent. It appears, therefore, that greater effectiveness of the ground cubé root and oil mixture than that which is indicated in tables 1 and 2 might be obtained if the mixture were stirred continuously for 20 minutes instead of 1 minute, as was done in the experiments recorded in this paper. However, extraction of the toxic constituents of the ground cubé root

TABLE 3

## EFFECTIVENESS OF CARDOLITE AS A SOLUBILIZER FOR DERRIS EXTRACTIVES IN KEROSENE\*

Treatment no.	Material	Kerosene deposit on leaves (ml/cm <sup>2</sup> ) <sup>10<sup>-6</sup></sup>	Net per cent survival†
Series A, sprayed April 9, 1942			
1	Kerosene without toxicant . . . . .	457.1	49.9
2	One part of freshly prepared oil-Cardolite-extractives solution to 39 parts of kerosene . . . . .	572.4	1.8
3	One part of kerosene-Cardolite-extractives solution prepared 6 weeks prior to use, to 39 parts of kerosene . . . . .	503.9	20.2
4	One pound of ground cubé root (200-mesh, 5 per cent rotenone) to 20 gallons of kerosene . . . . .	419.4	4.9
Series B, sprayed May 25, 1942			
5	One part of freshly prepared kerosene-Cardolite-extractives solution to 39 parts of kerosene . . . . .	576.5	2.9
6	One pound of ground cubé root (200-mesh, 5 per cent rotenone) to 20 gallons of kerosene . . . . .	318.5	1.7
7	One pound of ground devil's shoestring, <i>Tephrosia virginiana</i> (200-mesh, approximately 1.5 per cent rotenone) to 10 gallons of kerosene . . . . .	475.9	10.9
Least significant difference for odds of 19 to 1 . . . . .			
			8.4

\* Initial boiling point 360° F; end point 498° F, unsulfonatable residue 95 per cent plus. The kerosene, or kerosene plus toxic solution, was used in all plots at 10 per cent concentration with 4 ounces of calcium caseinate spreader to 100 gallons of spray.

† From 3,575 to 8,201 adult female red scales were examined in each plot. The treatments represented in this table were a part of the series shown in table 1, orchard A, and the least significant difference was calculated coincidentally with that of the data shown in table 1.

‡ The kerosene-Cardolite-extractives solution contains 75 per cent kerosene, 20.84 per cent Cardolite, and 4.18 per cent derris extractives (90 per cent rotenone).

continues to take place after the oil is placed in the spray tank if complete extraction has not been attained before (Ebeling and LaDue, 1943).

It can be seen from table 2, treatment 11, that a reduction in the amount of oil deposited on the tree overcomes the advantage resulting from the addition of the toxic solution and gives no better kill of red scale than that obtained from 2 per cent oil without a toxicant.

*Tests with Kerosene-Toxicant.*—The high degree of effectiveness of freshly prepared kerosene-Cardolite-extractives solution, when used at 10 per cent concentration in the control of the red scale (table 3), may appear paradoxical in view of the relatively fair less satisfactory results obtained when Cardolite is used as a solubilizer with the regular spray oils. However, as has already been mentioned, the presence of the extractives in a Cardolite-extractives-oil solution appears to be more effective than in a toxic oil solution. Sometimes only a low per cent of extractives is required to obtain

the desired insecticidal effect, as is the case when 10 per cent toxic kerosene spray is used against the red scale. In such cases, Cardolite affords an efficient means of preparing the toxic solution, for only a very small amount is required to incorporate the extractives into the oil as compared with the oleotropic solvent with which the writers have experimented.

The ability that Cardolite has of causing the beginning of an inversion of phases, or what Knight (1942) calls "unstable equilibrium" conducive to maximum oil deposit, may be one of the factors favoring its use in the kerosene spray; this increase in deposit is shown in table 3. Sometimes the Cardolite will even cause a doubling of oil deposit on the foliage of citrus trees when added to kerosene in the concentrations shown in table 3.

The amount of rotenone and deguelin extracted by kerosene when 1 pound of ground cubé root (95 per cent passing through a 200-mesh screen and containing 5 per cent rotenone) is added to 20 gallons of kerosene, stirred with a paddle, and allowed to stand for 20 minutes, is equivalent to that dissolved in the oil when 2 quarts of toxic Cardolite solution containing 4.16 per cent total derris extractives and 1.25 per cent rotenone is added to 19½ gallons of kerosene, namely, 0.05 gram per 100 ml. The two types of kerosene-toxicant spray have also, on the average, been about equally effective.

The kerosene-toxicant spray is discussed in this paper because of its academic interest only. The possibility of injury to the bark of citrus trees below the soil line if the kerosene is allowed to soak into the ground immediately adjacent to the trunk of the tree, and the occasional "gumming" of the trunk and branches of lemon trees, stand in the way of commercial use of kerosene sprays at 10 per cent concentration on citrus trees.

### DECOMPOSITION OF THE TOXICANT

The practicability of using finely ground cubé root with spray oil has been demonstrated. The oil-toxicant sprays containing only the ground root have the advantage of costing less per unit of rotenone plus deguelin dissolved in the oil, since the cost of extraction and preparation of a toxic stock solution is saved. Also the ground root can be stored for years without appreciable decomposition. Martin (1942) found no reduction in per cent of total extractives, rotenone, or rotenone plus deguelin when air-dried ground derris root was stored in tins for a period of from four to six years. On the other hand the rotenone-plus-deguelin content of an oil-Cardolite-extractives solution is reduced 24.4 per cent during the first month and is entirely decomposed at the end of 8 months (Gunther, 1943). This decomposition is largely eliminated by the addition of 1½ per cent by weight of hydroquinone. This indicates that the decomposition is largely an oxidation phenomenon, although since the pH of an aqueous solution of Cardolite 627 is 8.35, the basicity of the toxic stock solution accounts for some degree of decomposition (see Cahn, Phipers, and Boam, 1938a).

The effect of a 6-weeks' period of decomposition unimpeded by antioxidants is shown in table 3 by the great difference in net per cent survival of adult red scale in the plot in which a freshly prepared kerosene-Cardolite-extractives solution was added to the kerosene, as compared with an adjoining plot in which a 6-week-old solution containing the same proportions of ingredients

prepared in the same manner was used. The old solution was taken from a commercially prepared solution which had been stored in a 30-gallon drum on a spray-rig tender on which it had frequently been exposed to the direct rays of the sun. Probably many of the unsatisfactory results which have been reported in the commercial use of kerosene-toxicant spray in certain sections of southern California during the 1941 spraying season were caused by delay in the use of the toxic solution after its preparation. The results shown in table 3 indicate to what extent decomposition may unfavorably influence the results of an oil-toxicant spray. The decomposition of rotenone and deguelin in an oil-Cardolite-extractives solution is much more rapid than in *n*-butyl phthalate. As has already been shown (table 2), no significant reduction in the insecticidal effectiveness of a solution of *n*-butyl phthalate extractives could be demonstrated after a 54-day period.

#### THE APPARENT SYNERGISM OF ROTENONE AND ROHENONE-FREE EXTRACTIVES

Haller, Goodhue, and Jones (1942) have pointed out that although earlier work had indicated that rotenone was the most toxic of the extractives of derris root against certain insects, later work by H. A. Jones and associates had shown that powdered derris extractives containing about 25 per cent of rotenone were as toxic to mosquito larvae as was pure rotenone; also that F. L. Campbell *et al.* had found that a kerosene extract of derris from which no rotenone could be extracted was effective against houseflies. Bliss (1939) showed evidence of synergism of recrystallized rotenone and the "dehydro mixture" in the residual resin after the removal of the rotenone, in an evaluation of data from the experiments of Tattersfield and Martin (1935) on the toxicity of derris extractives to *Aphis rumicis*.

In table 4 are presented the results of a test to demonstrate the effect of (1) rotenone alone, (2) the rotenone-free extractives remaining when the rotenone is removed from the derris extractives (sometimes referred to as "deguelin concentrate"), and (3) the entire derris extractives (30 per cent rotenone) when used in regular oil spray and in kerosene oil spray, directed against the red scale. The rotenone was removed from the complete derris extractives by means of fractional crystallization of a carbon tetrachloride solution of the extractives. When used with 2 per cent light-medium spray oil, the toxicants were dissolved in *n*-butyl phthalate (table 4, plots 2, 3, and 4) and when used with 10 per cent kerosene spray the toxicants were dissolved in Cardolite (table 4, plots 6, 7, and 8), for reasons which have already been discussed.

In the light-medium spray oil, the same percentage of toxicant was used, whether it was rotenone, rotenone-free resins, or complete derris extractives. This was impossible when the kerosene-Cardolite solutions were used because it was impossible to maintain as high a percentage of rotenone in solution in the kerosene as of complete extractives. Therefore only as much rotenone was added as is ordinarily dissolved in the kerosene when the total extractives are added (1.25 per cent of the stock kerosene-Cardolite-extractives solution or 0.031 per cent of the finished kerosene-toxicant solution). Likewise as much of the rotenone-free extractives was added as is ordinarily dissolved in the kero-

sene when the total extractives are added (2.9 per cent of the stock solution or 0.072 per cent of the finished kerosene-toxicant solution). The usual toxic stock solution, which contains 4.16 per cent total derris extractives, was then added to kerosene at the rate of 1 quart to 9 $\frac{3}{4}$  gallons of kerosene. The finished toxic solution then contained 0.103 per cent total extractives, which is the sum of the per cent of rotenone in the solution used in treatment 6 and the per cent of rotenone-free extractives in the solution in treatment 7.

TABLE 4  
RELATIVE EFFECTIVENESS OF ROTENONE, ROTENONE-FREE RESINS, AND COMPLETE DERRIS EXTRACTIVES IN SPRAY OIL AND KEROSINE\*

Treatment no.	Material†	Concentration of extractives in the oil (per cent by weight)	Oil deposit on leaves (ml/cm <sup>2</sup> ) <sup>10</sup>	Net per cent survival‡
1	One part of <i>n</i> -butyl phthalate to 7 parts of oil (no toxicant) . . . . .		66.5	27.3
2	One part of a 5 per cent solution of rotenone in <i>n</i> -butyl phthalate to 7 parts of oil . . . . .	0.62	57.8	10.7
3	One part of a 5 per cent solution of rotenone-free resins in <i>n</i> -butyl phthalate to 7 parts of oil. . . . .	0.02	62.7	13.5
4	One part of a 5 per cent solution of total derris extractives to 7 parts of oil . . . . .	0.62	68.7	5.6
5	Kerosene alone (no toxicant) . . . . .	.	457.1	40.9
6	One part of a kerosene-Cardolite-extractives solution (with 1.25 per cent rotenone) to 39 parts of kerosene . . . . .	0.031	554.0	5.1
7	One part of a kerosene-Cardolite-extractives solution (with 2.0 per cent rotenone-free resins) to 39 parts of kerosene . . . . .	0.072	573.3	11.0
8	One part of kerosene-Cardolite-extractives solution (with 4.16 per cent total derris extractives) to 39 parts of kerosene. . . . .	0.103	572.4	1.8
	Least significant difference for odds of 19 to 1 . . . . .	.....	..	8.4

\* Specifications for spray oil and kerosene; and dates of treatment and examination, same as in tables 1 and 2.

† The spray oil or spray oil plus toxicant was used at 2 per cent concentration, and the kerosene or kerosene plus toxicant was used at 10 per cent concentration. No spreader was used with the spray oil, since it was of the emulsive type, and 4 ounces calcium caseinate spreader to 100 gallons of spray was used with the kerosene.

‡ From 4,334 to 8,783 adult female red scales were examined in each plot. The treatments represented in this table were a part of the series shown in table 1, orchard A, and the least significant difference was calculated coincidentally with that of the data shown in table 1.

The percentages of survival of red scales in treatments 2 and 3 (table 4) were not significantly different, indicating that in regular spray oil the rotenone-free extractives are approximately as effective as a similar concentration of rotenone when used against the red scale. Both toxicants result in a statistically significant increase in the effectiveness of the oil when present at a concentration of 0.62 per cent in the oil. A 0.62 per cent concentration of the complete extractives, however, resulted in a 5.6 per cent survival of red scale, which was significantly less than the per cent survival in treatments 2 and 3. The experiment indicates, first, that the rotenone-free extractives have a demonstrable toxic effect when added to spray oil by means of a suitable mutual solvent, which appears to be approximately equal to that of rotenone; and, secondly, that the combined toxic effect of rotenone and the rotenone-free extractives of derris extractives is greater than would be predicted from ex-

periments with the isolated constituents. In other words, there appears to be a synergistic effect when the different toxic ingredients of derris extractives are used together in their normal proportions. Another field test<sup>12</sup> not recorded in this paper has led to the same conclusion.

The 0.031 per cent solution of rotenone in kerosene resulted in a lower per cent survival (table 4) than the 0.072 per cent solution of rotenone-free extractives in kerosene, although again both solutions resulted in highly significant increase in the effectiveness of the oil. The total extractives at a 0.103 per cent concentration were more effective than the contained rotenone or rotenone-free extractives when used separately; but in this case no synergistic effect can be inferred because the per cent of total extractives was greater than the per cent of either the rotenone or the rotenone-free extractives. Unfortunately, a 0.103 per cent concentration of rotenone could not be used with the kerosene-Cardolite solution because that concentration of rotenone does not remain in solution.

#### COMPARISON OF TREATMENTS AT LONG PERIODS AFTER SPRAYING

Comparisons of treatments on the basis of per cent mortality or per cent survival immediately after treatment, or, as in the case of the red scale, a month after treatment, have been criticized on the basis that the relative effectiveness of treatments 6 months or a year after the application of the spray might be different from the apparent relative effectiveness based on per cent of insects immediately killed by the spray. In the case of oil sprays used against the red scale, this criticism is especially justified because of the effect of the oil residue left by the spray on the surface of the tree, which impedes the successful establishment and development of the newly emerged, motile young progeny of those scales not killed by the spray. The greater the volatility and penetrability of an oil, the less is the inhibition of settling and development of the crawlers because of the reduced amount of oil remaining on the tree surface. An oil which is about 60 per cent distilled at 636° F (light-medium spray oil), with the addition of a toxicant, might result in as great a per cent kill of red scale as an oil about 35 per cent distilled at 636° (heavy-medium spray oil), without the addition of a toxicant, if both oils were used at the same per cent concentration in the spray. However, if two plots had identical scale population densities at the time of treatment and one were treated with the light-medium oil plus toxicant and the other with the heavy-medium oil, the latter would have the fewer scales per tree 6 months or a year later, although the initial kills were equal in the two plots.

The inhibitory effect of kerosene is probably of no practical importance, because on a warm day the kerosene will disappear from the tree surface within a few hours by penetration and evaporation. This has prompted an investigation as to the long-term effectiveness of kerosene plus toxicant as compared with regular spray oils even though the kerosene should result in a higher degree of initial effectiveness as based on per cent kill.

*Observations in a Heavily Infested Lemon Orchard.*—A lemon orchard in Covina, California, heavily infested with red scale, was selected for an experi-

<sup>12</sup> Data on file at the University of California Citrus Experiment Station, Riverside, California.

ment to determine the relative effectiveness, at long periods after application, of treatments which differ greatly in their ability directly to kill the red scale. Thirteen randomized plots, each with three subplots, were sprayed with various oils and kerosene with and without toxicants. Among these plots were the following: plot 1, 10 per cent kerosene-toxicant with 1 quart of kerosene-Cardolite-derris-extractives stock solution (see footnote 11) to 9½ gallons of kerosene, toxicant A; plot 2, 10 per cent kerosene-toxicant with 1 pint of the

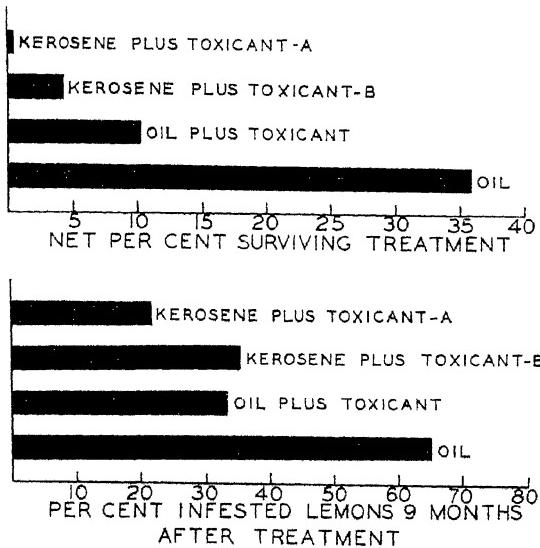


Fig. 2.—Relative effectiveness of four different treatments against the red scale in a heavily infested lemon orchard as shown by net per cent kill of adult female red scales on the branches of the trees a month after treatment (upper) and per cent of fruits found to be infested with red scale 9 months after treatment.

toxic stock solution to 9½ gallons of kerosene, toxicant B; plot 3, 2 per cent light-medium oil with ½ pint of oil-Cardolite-extractives stock solution to 1½ gallons of oil; and plot 4, 2 per cent light-medium oil. Four ounces of calcium caseinate spreader to 100 gallons of spray was used in each plot.

The results of the experiment are shown in figure 2, where is depicted the relative effectiveness of the four treatments as based on per cent kill immediately after treatment and per cent of infested fruit on the trees 9 months after treatment. The treatments were applied November 18, 1941, and examinations to determine the per cent kill were made a month later. Then on September 1, 1942, four subplots, representing four different treatments which happened to be closely grouped in an area of the orchard in which the original population was reasonably uniform, were compared for relative infestation. All lemons less than 10 feet above the ground, on each of 10 trees in each subplot, which were more than half grown (about 1 inch in diameter) were examined and recorded as to whether they were free of red scales or infested. All the lemons which could be examined from the ground were counted, and simultaneously the number infested was determined.

The net percentages of adult females surviving the spray treatments (as based on counts made a month after treatment) in each plot were as follows: plot 1, 0.45; plot 2, 4.5; plot 3, 10.2; and plot 4, 36.1. These percentages represent the average of three subplots. The percentages of infested fruit on the trees 9 months after treatment, as determined by observations of four adjacent subplots, were as follows: plot 1, 22.4; plot 2, 34.9; plot 3, 31.6; and plot 4, 64.9. Of the net percentages of survival, all were significantly different from one another according to an analysis of variance; of the percentages of infested fruits 9 months later, all were significantly different from one another except that plot 3 was not significantly different from plot 2.

It should be borne in mind in the evaluation of the data presented in figure 2 that the relative lengths of the bars in the lower part of the figure show only the relative percentages of infested fruits, not the relative population densities. The plots having the greater percentages of infested fruits also appeared to have, from general observation, a greater average number of scales per fruit.

It is to be expected that, with passing time, differences in population density immediately following spraying would become increasingly smaller, resulting eventually in a complete obliteration of differences when all fruits on the tree become infested. In commercial procedure, of course, the orchard is usually treated before such a degree of infestation prevails. The rapidity with which the differences between plots are evened out depends on the original population density and the percentages of scales surviving the treatments, for the greater the number of scales in the plots following treatment, the sooner a condition will be reached wherein practically all fruits are infested.

It will be noted in figure 2 that although in the plot sprayed with spray oil plus toxicant (treatment 3) the net per cent survival was over twice as high as in one of the plots sprayed with kerosene plus toxicant (treatment 2), there was no significant difference in the per cent of infested fruit in the two plots 9 months after treatment. Thus the residual effect on the crawlers emerging from the scales not killed by the oil-toxicant spray offset the lesser immediate insecticidal effectiveness of the oil plus toxicant as compared with the kerosene plus toxicant. However, the plot sprayed with 10 per cent kerosene-toxicant with 1 quart of toxic solution to 9½ gallons of kerosene (treatment 1), which resulted in the best kill of scales, was also the least heavily infested of all plots 9 months after treatment. This shows that a sufficiently high degree of initial kill with a material not having a long-term residual effect can overbalance in importance the advantage due to the residual effect possessed by less volatile oils.

*Observations in a Heavily Infested Orange Orchard.*—On October 21, 1942, an attempt was made to evaluate the relative effectiveness of some of the red-scale treatments applied to the heavily infested orange orchard sprayed April 9, 1942, the initial results of which, in terms of the percentages of insects surviving the treatment, were summarized in table 1 (orchard A, treatments 1 and 3) and table 3 (treatments 1 and 2). As can be seen from the tables, the per cent survival immediately after treatment was as follows: for the oil alone, 25.1; oil plus toxicant, 5.6; kerosene alone, 49.9; kerosene plus toxicant, 1.8. The examination of the plots in October revealed that all fruits on the trees sprayed with oil alone or kerosene alone were infested, but so were nearly

all the fruits on the trees sprayed with oil-toxicant or kerosene-toxicant. It was obvious, however, that the fruits in the plots sprayed with oil alone and kerosene alone were on the average more heavily infested than the fruits in the plots sprayed with oil-toxicant or kerosene-toxicant. Therefore, a determination of the number of scales per fruit would have been necessary to indicate the relative degree of infestation.

A random sampling of leaves, however extensively made, would not afford an accurate criterion of relative population densities because the leaves, after they are heavily infested, turn yellowish and finally drop to the ground. In October the leaves in the oil-sprayed plot had begun to drop to an appreciable extent, while in the kerosene-sprayed plot severe defoliation had already taken place. No abnormal defoliation occurred in plots in which toxicants were added to the spray. Thus, 6½ months after treatment, a general observation of the plots afforded a more adequate means of evaluating the long-term effectiveness of the treatments than any practicable statistical evaluation.

It will be noted that even those treatments resulting in the highest degree of control were not sufficiently effective to keep the fruit from being infested, and consequently made unmarketable, 6½ months after the treatments were applied. It must be borne in mind, however, that the orange orchard in question was extremely heavily infested at the time of spraying, and even a 99 per cent kill in such an orchard leaves large numbers of scales to reproduce in the tree. In an orchard of average infestation, it is common knowledge, an effective treatment may result in scale-free fruit even a year after treatment, while a materially less effective treatment in the same orchard, applied at the same time, may result in such a rapid reinfestation of the orchard that within a year the marketing value of the fruit may be greatly reduced.

## DISCUSSION

Although the contributions of McBain and associates (1940, 1941, 1942) are most obviously related to the large and important fields of detergency and dyeing, their penetrating analysis of the theoretical implications of solubilization, as contrasted with ordinary molecular solution enhanced by the addition of hydrotropic or oleotropic solvents, can contribute much to a better understanding of the problems confronting oil-spray-research workers who are attempting to add oil-insoluble toxicants to oil.

The solubilizers are as a group relatively complicated, long-chain compounds as compared to the simpler oleotropic solvents such as *n*-butyl phthalate and diamyl phenol. Thus, for example, Cardolite 627 has a branched unsaturated chain of 14 carbon atoms attached *meta* to the -OH group of phenol. Solubilizing detergents are of similar complexity. In fact, McBain and Merrill (1942) believe that the effectiveness of a compound as a solubilizer increases with chain length to a limit fixed only by the necessity for having the solubilizer itself in solution. This difference in the chemical nature of the solvents may be used, at least roughly, as a guide in the selection of mutual solvents, according to the particular goal of the investigator.

Judging from the experience the present writers have had, true solubilization, despite its extreme efficiency in bringing about a visually clear and stable colloidal solution of clerris or cubé extractives in the oil, should be avoided in

the preparation of oil-toxicants except when low concentrations of the extractives are adequate to bring about the desired insecticidal effect, as with the kerosene sprays of the present investigation. The possibility is not excluded, however, that further research may change or modify this belief.

It may be concluded, from present knowledge of the nature of solubilization, that insecticidal effectiveness, presuming identical concentrations of extractives in the oil-toxicant solution, is probably proportional to the true molecular concentration in the solution; this is probably greater when oleotropic solvents are used as mutual solvents than when solubilizers are used, for even though a larger amount of extractives is brought into solution by the latter, most of it is in colloidal solution and not in true molecular solution in the continuous liquid. Furthermore, from one fourth to one third of the rotenone-plus-deguelin content of an oil-toxicant having Cardolite as a solubilizer was found to pass from the oil to the water phase of an oil-water mixture agitated for 45 minutes.

Presumably the molecules of extractives bound within the colloidal micelles of a colloidal solution effected by means of a solubilizer are not so available for effect on the insect tissues as they would be if they were in molecular solution. As far as our present information indicates, however, molecular solutions of derris or cubé extractives in oil can be made only by (1) dissolving powdered extractives, or soaking the finely ground root of derris or cubé, directly in the oil; or (2) by using oleotropic solvents, which, as they are added, progressively increase the solubility of the extractives in the oil until in large quantities they make possible an adequate concentration of the extractives in molecular solution in the oil, besides effecting a stable suspension of a large percentage of the remaining extractives in extremely small particles, which, however, are not bound within colloidal micelles.

It is possible that the most effective mutual solvents, from the insecticidal standpoint, might leave a portion of the extractives in suspension when added to oil in the proportions which would appear to be practical either from an economic standpoint or from the standpoint of their effect on fruit or foliage.

The use of Cardolite as a solubilizer, as has been stated before, was first encouraged by the fact that visually clear and stable solutions of extractives could be formed in the oil, whereas with other solvents a certain cloudiness occurred even when exorbitantly large quantities of the solvents were used. In the latter case a completely ready-for-use oil-toxicant solution could not be manufactured because of the settling of the suspended material in the drums in which the oil was stored, which, if nothing else, resulted in a gummy residue in the drums which ruined them for further use. Kagy and Boyce (1941) have shown that a certain amount of precipitation does not necessarily indicate a reduction in toxicity because the toxic ingredients may remain in solution in the oil.

From the standpoint that stable solutions are more amenable to proprietary exploitation than partial suspensions, the solubilizers lend themselves more readily to commercial use than oleotropic solvents. Trials with Cardolite as a solubilizer for incorporating derris extractives into the heavier spray oils, however, showed inconsistency in results. In no case were results so good as might be expected on the basis of earlier work with the same amounts of oil

and extractives, but with *n*-butyl phthalate as a mutual solvent. The data presented in this paper further illustrate the superiority of the oleotropic solvents.

If sufficient advantage in the way of insecticidal effectiveness is found in the use of oleotropic solvents, it might, apparently, be advantageous to prepare the mutual solvent-extractives solution separately from the oil and add it to the oil immediately before use. However, it is possible that a way may be found to use Cardolite, or other solubilizer, in spray oil in a manner that will permit a more efficient utilization of the solubilized extractives at the higher concentrations.

It has been shown in this paper that a high concentration of rotenone plus deguelin in light-medium spray oil may be obtained merely by soaking finely ground cubé root in the oil for 20 minutes, while stirring vigorously. The advantages of this method of dissolving the extractives in oil are that (1) the extracted toxic constituents of the root are entirely in true molecular solution, in which condition they have their greatest possible insecticidal value; (2) the danger of foliage injury or reduction in oil deposit which may be caused by a mutual solvent is eliminated; and (3) the method is the most economical of all known means of incorporating derris or cubé extractives into spray oil. Cubé extractives, however, are more easily extracted from the ground root than are derris extractives.

#### SUMMARY

Powdered extractives of rotenone-bearing plants may be dissolved directly in spray oil at room temperature in concentrations of insecticidal value by mixing the powder in oil for a 20-minute period. In the same manner the extractives may be obtained from finely divided plant material. In either case an emulsive oil was found to be a better solvent for the extractives than straight oil of the same grade; and to obtain the highest concentrations in oil, mutual solvents must be used.

A *solubilizer* is a mutual solvent which in very dilute concentration, usually 1 per cent or less, will produce a thermodynamically stable colloidal aqueous or nonaqueous solution of otherwise insoluble or only slightly soluble substances.

The term *oleotropic solvent* is proposed for mutual solvents which, when added to an oil in large amounts, will increase the solubility of an otherwise insoluble or slightly soluble substance in oil merely by adding their solvent properties to that of the oil.

No rotenone plus deguelin was found to have passed from the oil to the water phase of an oil-water mixture agitated for 45 minutes when the extractives were in true solution in the oil. However, under the same conditions a colloidal solution of extractives in oil may lose from one fourth to one third of its rotenone-plus-deguelin content in an oil-water mixture agitated for 45 minutes.

Cardolite 627 is a highly efficient solubilizer for incorporating derris extractives in spray oil, forming a visually clear, stable solution which is probably mainly colloidal; but *n*-butyl phthalate, as an example of a good oleotropic solvent, will form a slightly cloudy solution when 5 per cent derris extractives

in *n*-butyl phthalate is added to spray oil at the rate of 1 part to 7 parts of oil. Nevertheless an oil spray with an optimum concentration of derris extractives brought into partial solution in the oil by means of *n*-butyl phthalate as a mutual solvent is far more effective against the California red scale than an oil spray used at the same strength and containing the same concentration of derris extractives, but having Cardolite 627 as a solubilizer.

The increase in the insecticidal effectiveness of the oil due to the addition of a solution of *n*-butyl phthalate extractives is brought about despite the reduced amount of oil deposited on the tree surface because of the emulsifying effect of the mutual solvent.

It is assumed that the greater insecticidal effectiveness of the oil-toxicant solutions containing oleotropic solvents, as compared with those containing solubilizers, results from the fact that the molecules of extractives are mainly in molecular solution; in this condition they are probably more effective against insect tissue than when they are bound within the lamellar micelles or otherwise constituted colloidal particles resulting from solubilization. Likewise, as stated before, a substantial proportion of the colloidal particles will pass from the oil to the water phase of an agitated spray mixture if the extractives are in the oil in the form of a colloidal solution.

Freshly prepared kerosene-Cardolite-extractives solutions are highly effective against the red scale when added to kerosene to make a 0.103 per cent concentration of total extractives (0.031 per cent concentration of rotenone) in the kerosene. A 6-weeks' period was sufficient to cause considerable decomposition of the toxic solution in which Cardolite was used as a solubilizer. This decomposition can be minimized by the addition of an antioxidant.

An adequate concentration of derris or cubé extractives can be obtained merely by soaking ½ pound of finely ground derris or cubé root in 10 gallons of kerosene for 20 minutes. This results in a concentration of rotenone plus deguelin in the kerosene of 0.05 grams per 100 ml. The finely ground root also increases the effectiveness of regular oil spray when added at the rate of 4 ounces to 1 gallon of regular spray oil, but in the field work reported in this paper the ground root has not been stirred in the oil for a sufficiently long period to result in the maximum concentration of rotenone plus deguelin in the oil. A continuous stirring of ground cubé root in emulsive spray oil for 20 minutes will result in the maximum degree of extraction of the toxic ingredients from the root particles, and, if such a procedure were practiced, it is probable that the ground root soaked directly in the oil would afford the most effective practicable means of using this product with spray oil against citrus pests. The toxic ingredients of derris root are not so readily extracted by spray oil as those of cubé root.

When added to spray oil, the rotenone-free extractives (deguelin concentrate) of derris appear to be about as effective as rotenone when identical concentrations of each are used. However, the complete extractives are more effective than equal concentrations of either the rotenone or the rotenone-free extractives used by themselves; evidently the latter two are synergistic. When added to kerosene the rotenone-free extractives were not so effective as the rotenone, even though the latter was of necessity used at a lower concen-

tration; neither were they so effective as the total extract at 330-32.  
same concentration.

It may be that the best mutual solvents, from the standpoint of commercial effectiveness, will not lend themselves to the preparation of finished-for-use spray oils with toxicants because a certain percentage of solids precipitate upon standing. If this be the case, it is suggested that the mutual solvents and extractives be prepared in a separate solution to be added to the oil just before the oil is poured into the spray tank.

An oil film on the tree, impeding the settling and development of "crawlers" issuing from scales not killed by an oil spray, was demonstrated to influence markedly the effectiveness of the treatment 9 months after spraying when the oil-toxicant spray was compared with a kerosene-toxicant spray, which leaves no oily residue because of rapid penetration and evaporation of the kerosene. However, when the initial per cent of kill from a kerosene-toxicant spray was sufficiently high (99.5 per cent) it more than offset the disadvantage of lack of oily residue, and resulted after a 9-month interval in trees more free of scaly lemons than those sprayed with the regular light-medium spray oil with or without a toxicant.

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